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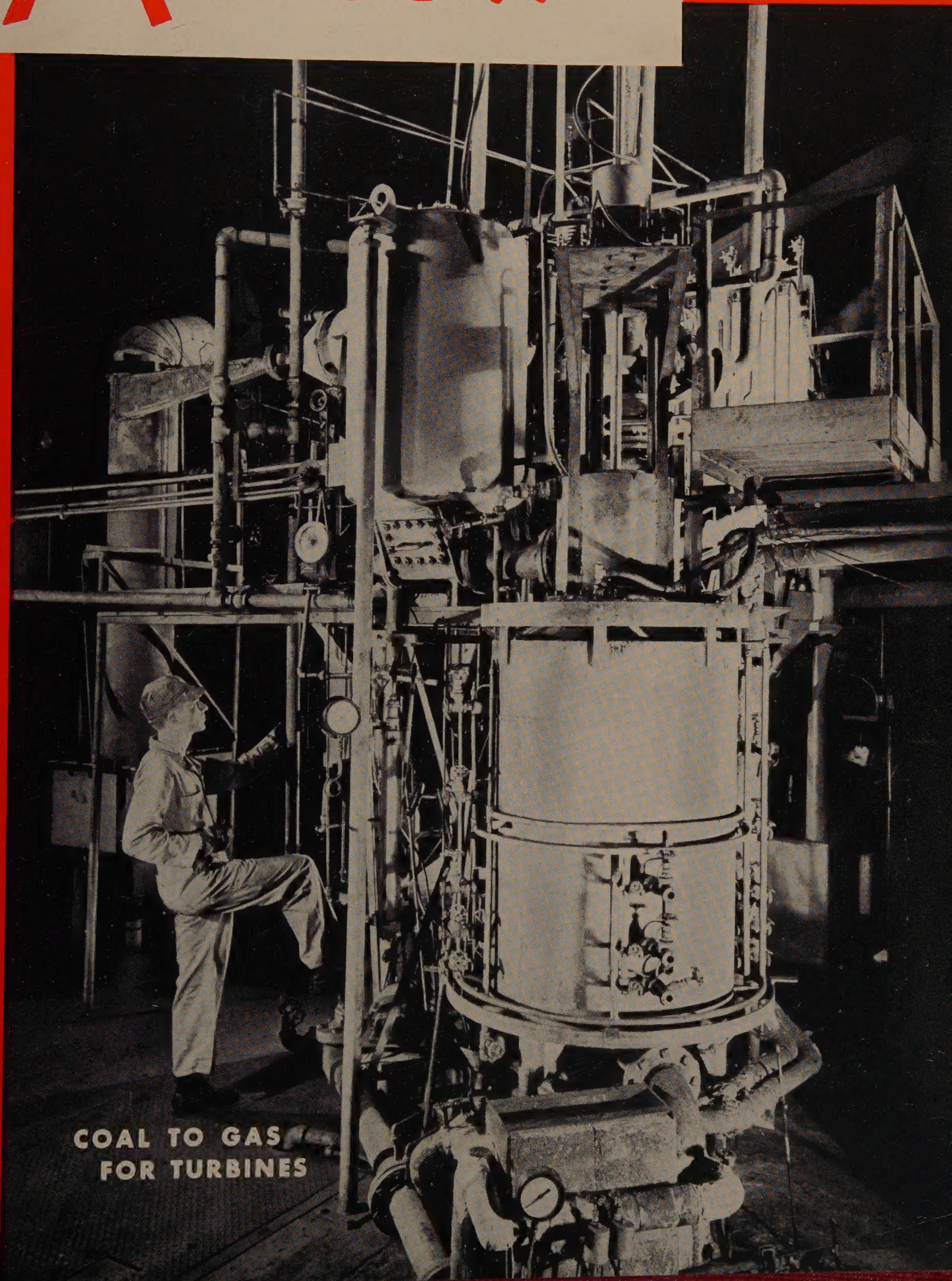

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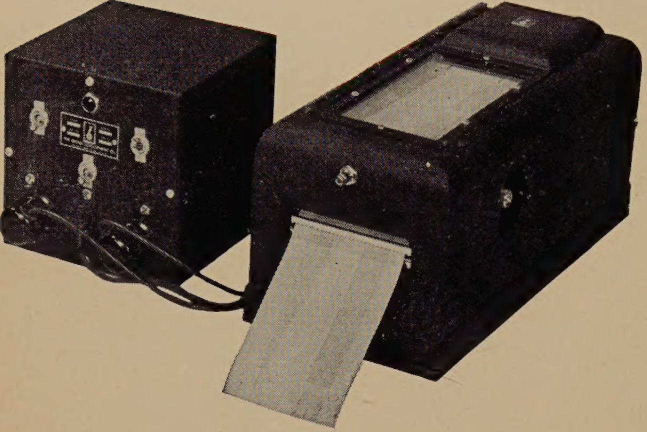

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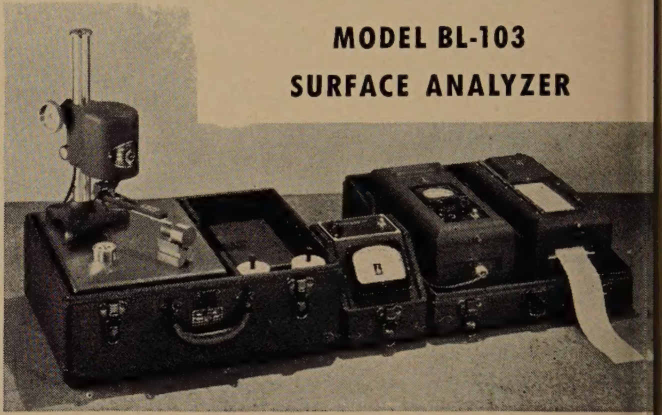

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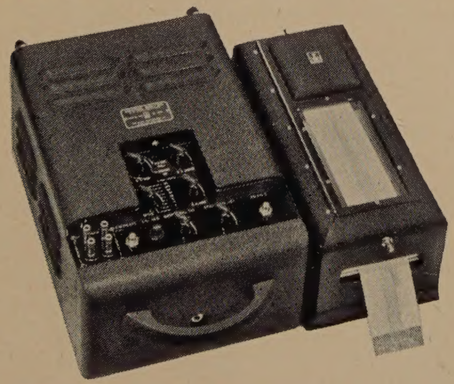

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GENERAL ELECTRIC Review

DECEMBER, 1951
Vol. 54, No. 12

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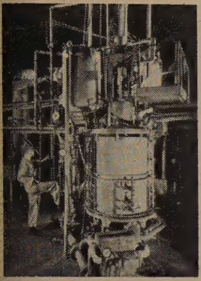

THE COVER

s turbine fuel from cheap and abundant coal
promise of a new and useful addition to the
able prime movers—a coal-burning gas turbine
. Among the possible means of utilizing this
one that has been extensively investigated is
ication under pressure in a gas producer and
ing the resultant gas. The gas-producing equip-
shown here is used for making gas from
ninous coal. Development of the process,
acteristics of fuel, and some special problems
stigated in the gasification process are described
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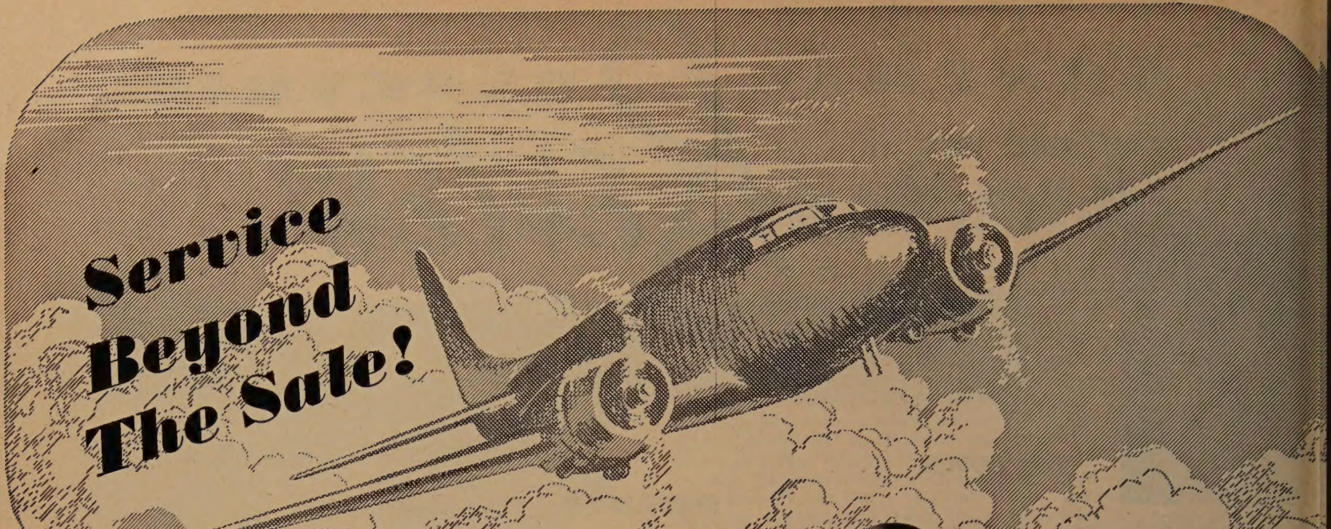
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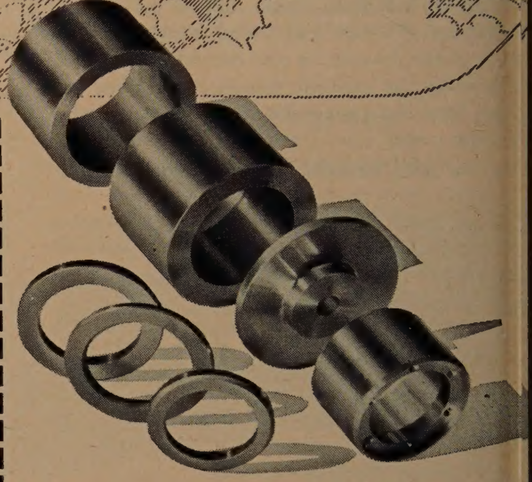

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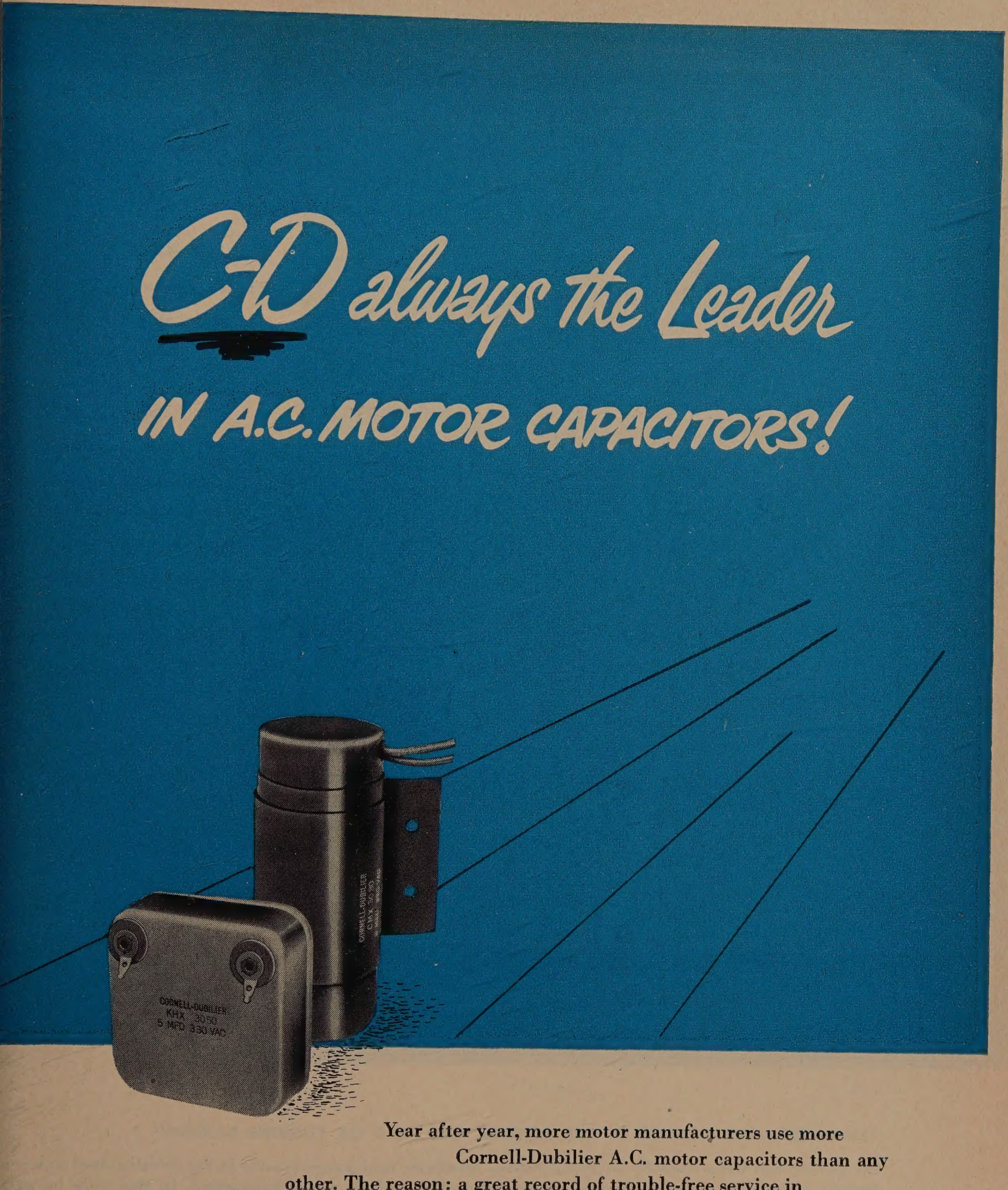
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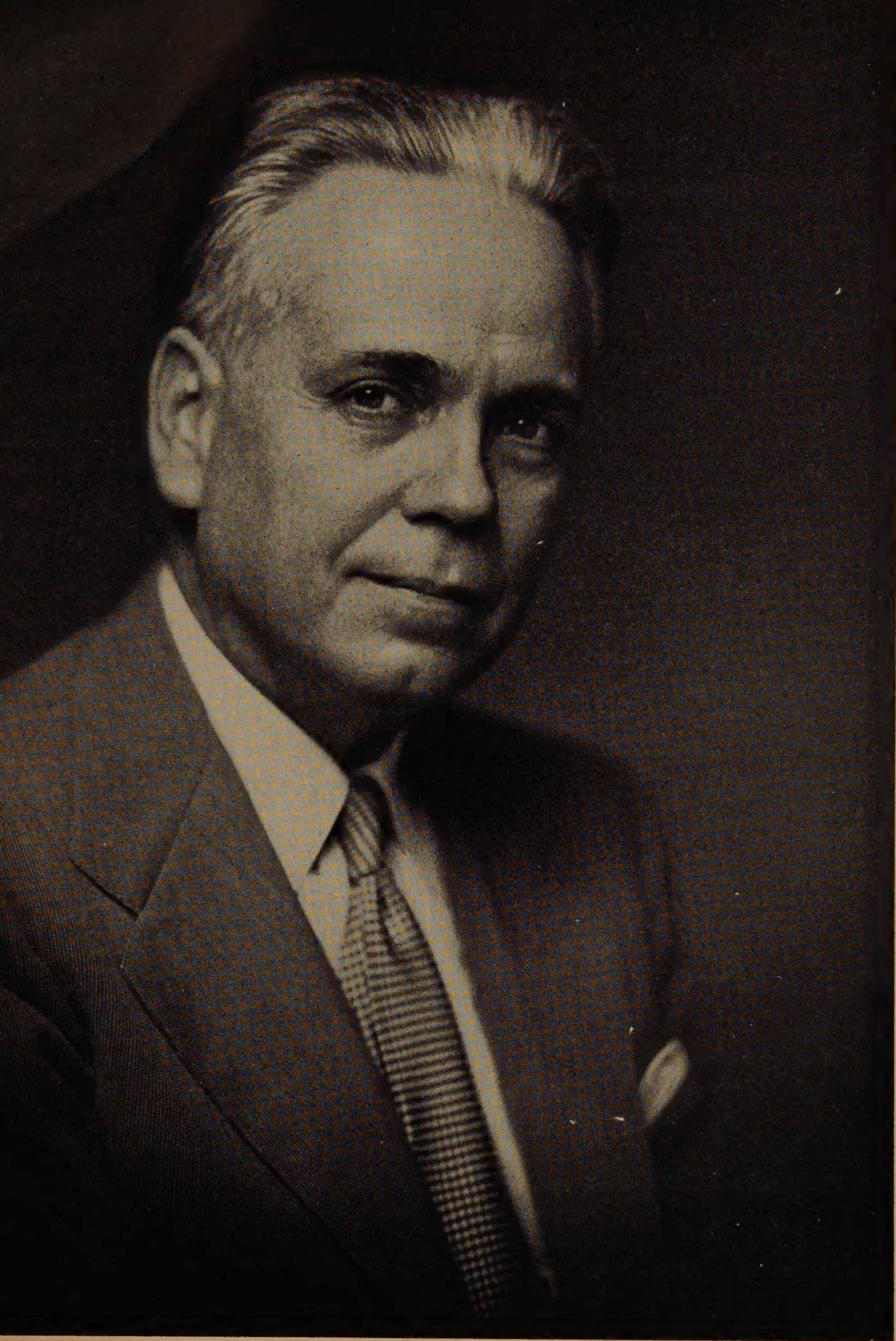

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GENERAL ELECTRIC Review

DECEMBER
1951

To Our Readers:

Since 1903 the General Electric Review has made available engineering and scientific information toward the advancement of electricity into every possible avenue for the benefit of mankind. To read the pages of the Review over the years is to see the works of men in engineering and science, to appreciate anew the wonders of their accomplishments, and to gain a more profound realization of the importance of their work of today as we consider the extent of future achievement.

The General Electric Review of today is of limited circulation. We want to extend to a larger audience its long established reputation as a professionally authoritative magazine. Therefore, beginning with the January 1952 issue, it will be distributed without subscription cost to an extended list of interested friends of the General Electric Company. This December issue is thus the last under the present circulation policy.

We are not saying good-bye to old friends; we are saying hello to many new ones.

The new Review will be published bimonthly beginning with the January 1952 issue. It will continue, as in the past, to make available useful information and ideas concerning research, products and engineering developments, designs, applications, methods, and techniques.

Sincerely,

Everett S. Lee, *Editor*

PRODUCER GAS FOR GAS TURBINE

By
BRUCE O. BUCKLAND
ARTHUR Y. HILLMAN, JR.
Turbine Engineering Division
General Electric Company

and

HARLAN W. NELSON
Battelle Memorial Institute
Columbus, Ohio

Bruce O Buckland

Arthur Y. Hillman Jr.

Harlan W. Nelso

ONE feasible way of using coal in a gas turbine is to gasify it under pressure and to supply the resultant gas to the gas turbine. The pressure produced by a gas turbine compressor (5 to 9 atmospheres) should allow the use of high firing rates without unreasonably high solid carry-over rates. Hot make-gas with the tars contained in it in the vapor form can be used in a gas turbine. Most of the ash is removed through a grate, and only a small portion of the ash and any of the solid combustible material carried over by the make-gas requires separation. The gas stream from which separation is required is a small portion of the total flow of a gas turbine plant and hence the separator size will be small. The gas stream is reducing and will not, therefore, allow separator fires to occur. The response of the producer to rapid load changes is such that the control equipment necessary to regulate the coal feed and the steam addition to the blast relatively simple.

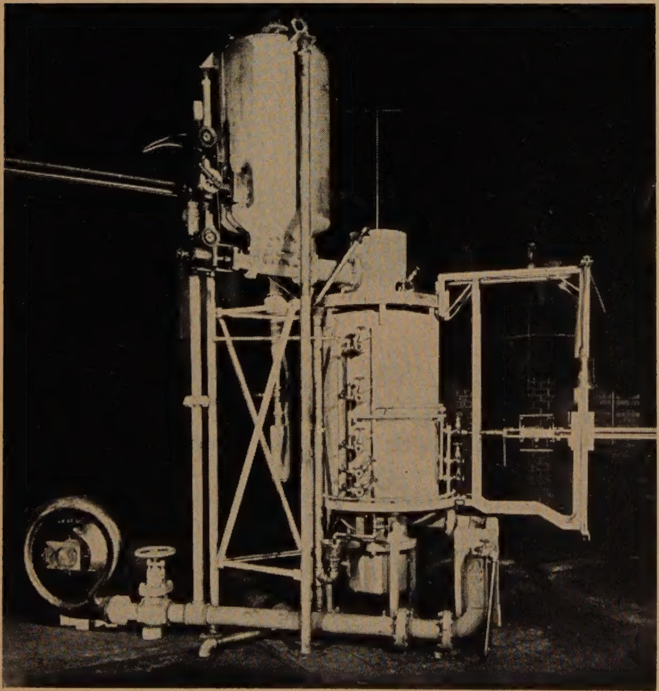


Fig. 1. Developmental producer and associated equipment used in earlier tests

With these factors in mind, the Steam Turb Division of the General Electric Company made rangements with Battelle Memorial Institute to vestigate the problems of the gasification process. a meeting in January 1945, at Schenectady, of rep sentatives of the two organizations, it was decided proceed with the investigation at a modest rate means of tests on a small-scale gas producer. Pl were made to test with coke and bituminous coal. T

TABLE I: FUELS USED IN PRODUCER TESTS

Coal Seam	Ash Percent	Ash-softening Temp F	Caking Propertie
Millers Creek	3 to 5	2100 to 2360	Slight
Ohio No. 8	5 to 8	2130 to 2280	Strong
Illinois No. 5	15 to 18	2000	Modera
Pittsburgh (W. Va.)	14 to 15	2360	Strong
High-temperature coke	11	2540 to 2690	None

test producer was to be built with one square foot grate area and was to be operable at one to six atm pheres pressure.

The project was organized, the test apparatus a the test producer were designed and built, and January, 1946, the first test was run. A total of tests have since been run, 26 with coke and 67 w bituminous coal. Fuels covering a wide range of contents, ash-softening temperatures, and caki properties have been used as listed in Table I.

As a help in this project and to get a coal both hi in ash and strong in caking qualities, the Pittsbur (W. Va.) seam coal was supplied by an electric util company.

The tests were run on the small-scale producer define approximately the performance and the limi tions of a gas producer working under pressure supply fuel for the operation of a gas turbine and indicate, in so far as possible, the requirements of t design of a full-scale producer. The effects of pressu rate of gasification, fuel properties (for three produ

---

Presented at the Semiannual Meeting of the American Society of Mechanical Engineers, St. Louis, (Mo.), June 19–23, 1950.—EDITOR.

angements and modifications) as well as preheat l rapid load changes on operation problems (clinker-, coking, channeling, carry-over, and make-gas ality) were investigated. This paper describes the all-scale gas producer and the test equipment used, l presents briefly the results of the tests.

TEST EQUIPMENT

'IG. 1 shows the producer and its associated equip-nt; FIG. 2 is a schematic drawing of the equipment its initial form and before the first modification.

The gasification furnace consists principally of three ts: the main shell, the top bell, and the ash receiver. e cylindrical main shell, 32 in. in diameter, lined h 9½ inches of refractory and insulating brick, ms a retort 13½ in. in diameter. The height of the ort is sufficient to hold a 42-in. deep fuel bed above finger grate which forms its bottom. The conical mber of the main shell, cooled with water coils (*17*) he outlet of the retort to which the gas offtake pipe velded. The top bell, which is also water-cooled, is ted to this conical member. It carries a manually rated and water-cooled bed-leveling device which ves also as a bed-level indicator. The bell has an ning in the side for the attachment of the fuel ew (*13*), and an inspection hole in the top for ex-ining the top of the fuel bed. The combustion air admitted through an extension of the main shell ow the grates, and to this extension the ash receiver) is bolted. It also has an inspection hole through ich the character of the ash can be seen as the grates shaken.

Air supplied by the compressor (*2*) through the 57-ft receiver (*4*) is regulated by the control valve (*5*). hough not shown in FIG. 2, provision is made for admitting steam with the combustion air. The fuel is supplied from a pressure-tight hopper (*11*) by means of a four-inch variable-speed feed screw (*13*). The hopper has a capacity of 500 lb of fuel, and can be easily removed for weighing.

Fourteen flanged and valved connectors (*18*) are attached to $1\frac{1}{16}$-in. holes through the main shell and lining, to accommodate a transferable gas-sampling probe (*20*). The connectors also allow a bed-temperature probe to be used. They are arranged in three vertical columns spaced 90 degrees apart horizontally and at intervals from 1.5 in. to 42 in. above the grate vertically.

The gas produced is passed through a separator (*8*), for the removal and measurement of carry-over, to the throttle valve (*9*), where the pressure is dropped to one atmosphere. Gas samples can also be collected in the brine bottles (*22*).

Auxiliary Equipment and Instrumentation

FIG. 2 shows the water-cooled gas-sampling tube (*20*) connected to one of the sampling ports of the generator. The tube is supported by a fixture (*24*), arranged to permit the vertical, radial, and peripheral motion required to connect it to the openings in the generator. Gas samples from various points in the fuel bed are obtained by inserting the tube through a valve-and-locking arrangement into the proper port to the desired depth. The over-all diameter of the sampling tube is ⅝ in., which enables manual insertion of the tube against the pressure within the generator. For runs under pressure, the rate of withdrawal of the sample is regulated by throttling with the needle valve (*18*). The gas is collected over brine in a set of sampling bottles (*22*), unless samples are to be stored more than a few hours; these are collected over mercury.

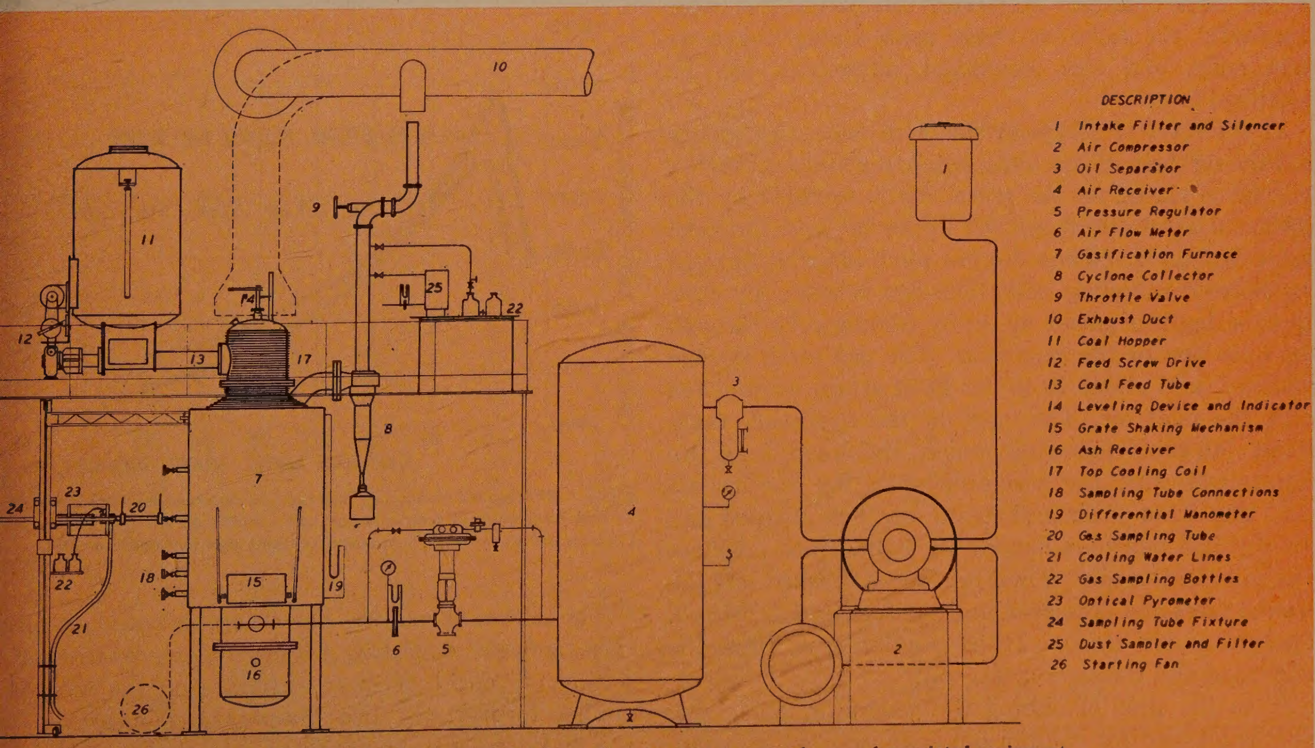


Fig. 2. Schematic drawing of initial form of developmental gas producer and associated equipment

Provision is also made for taking continuous make-gas samples during a run. This gas is collected just ahead of the main throttle valve (*9*) and is stored in bottles (*22*) for analysis.

The temperatures of the fuel bed at the various sampling locations are obtained as follows: A sight path to the desired point of measurement in the fuel bed is cleared by inserting the gas-sampling tube to the proper depth. The tube is then withdrawn and disconnected from the sampling port. A sight glass is attached in its place and the temperature at the desired point is obtained by sighting on the bed with an optical pyrometer.

The temperatures of the inlet air, steam, and steam-air mixture are taken with standard thermometers placed in oil-filled wells located in the lines carrying these fluids. A chromel-alumel thermocouple used with recording potentiometer gives a continuous record of the make-gas temperature during a run. The thermocouple, which is jacketed in a stainless-steel tube, is located in the generator off-take pipe just ahead of the throttle valve.

The weight of fuel fed into the generator during a test is obtained directly by weighing the hopper and contents both before and after the run. Rates of flow of air and steam are obtained by using calibrated fluid orifices located in the respective lines. The steam-air ratio is then calculated from the weight of steam flowing per hour plus the moisture entrained in the inlet air, divided by the weight of air flowing per hour. The rate of fuel fed is adjustable by means of the variable-speed drive used on the fuel screw.

Method of Operation

The method of operating the producer varied somewhat as different fuels were used and as the objective of the tests changed. However, the procedures were essentially the same as those used during the tests with coke, and any significant differences will be described later.

At the start of a typical test with coke, the hopper and the top bell are disconnected, and about four inches of coke is placed on the grate. Air is supplied by the blower at a rate of about 180 lb per hr, and the coke bed is ignited by means of a gas torch inserted through the bottom sampling port. The bed is gradually built up to a depth of about 40 in. by feeding coke through the open top of the generator. The gas torch is then removed, and about 10 lb per hr of steam is admitted with the inlet air. This part of the operation takes about 30 min, following which the conditions are maintained with the producer open for another 45 min. The flows of air and steam are then stopped and the top bell and feed hopper are bolted into position. The air and steam flows are re-established at the desired rates and pressures, and the fuel feed is started. The grates are shaken at 10-min intervals from the beginning and throughout the run.

From the time of closing the generator, about one hour is allowed for equilibrium conditions to be established in the fuel bed, during which time the make- is analyzed for CO_2. Thereafter, the test proper considered to have started and gas samples are ta from the bed according to schedule. The make-ga sampled continuously and analyzed at 30-min interv

The time required for the test proper is about th hours. At the end of the test the air flow is stopp but steam is admitted for about one hour longer cool the bed. The following day the fuel bed is dump and the amount, size, and distribution of clinker noted.

The weight of carry-over material during a run determined periodically during the test proper means of twin cyclone separators. The cyclones water-jacketed, and the water is kept at the boili point at all times to prevent condensation of un composed steam. The collectors are detached cleaned just before the collection period begins. Af a collection period of 10 to 20 min, depending the air rate, the collectors are again detached from cyclones, and the carry-over is dumped, weighed, screened.

TESTS WITH COKE

The initial tests were made with high-temperat coke in order to avoid the difficulties to be expec from caking and from tar formation when bitumino coals are gasified. Twenty-four tests, as follows, w run with the pea-sized coke described in Table 13 at 1 atmosphere; 5 at 3 atmospheres; 4 at 6 mospheres; and 1 each at 5 and 7 atmospheres. T first 5 tests, 4 at 1 atmosphere and 1 at 3 atmospher were made to develop gas-sampling techniques and establish the test procedures. Table III gives t operating conditions of the remaining 19 tests.

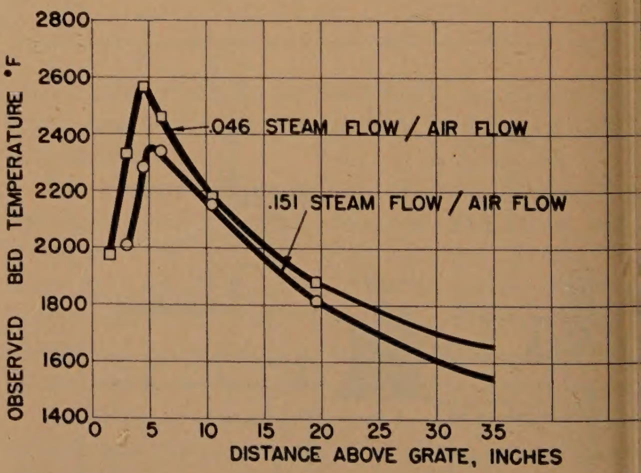


Fig. 3. Effect of steam flow/air flow ratio on observed fuel-bed temperatu 90 min after start of test. Average test conditions: air rate, 200 lb per preheat, 200 F; pressure, 1 atmosphere; fuel, high-temperature coke

The effects of varying the steam-air ratio, the bl rate, and the operating pressure were determined noting the effect of these variables on the amount clinker formed, the bed temperatures measured, a the make-gas quality obtained.

BLE II: PROPERTIES OF HIGH-TEMPERATURE COKE USED IN GAS PRODUCER TESTS

(Size ¾ × ⅜ in.)

	Lot 1	Lot 2
ximate analysis, as fired, percent		
Moisture	0.5	0.0
olatile matter	1.5	1.0
ixed carbon	87.1	87.8
sh	10.9	11.2
otal	100.0	100.0
-fusion properties		
nitial deformation temperature, deg F	2560	2260
sh-softening temperature, deg F	2690	2540
luid temperature, deg F	2740	2680

nker

During early tests with steam-air ratios of about 07, the slag solidifying on the refractory wall in the ver part of the producer made it difficult to insert e sampling probe, particularly toward the end of the st. After the four-hour operating period of Test 9, example, at a steam-air ratio of 0.072 and an air e of 298 lb per hr, all but a 3-in. diameter opening the center of the bed was occupied by a ring of nker. The ring projected about four inches inward dially and extended upward a distance of about r inches from a point three inches above the grate. displaced the reaction zones upward, and adversely ected the quality of the gas.

Increasing the steam-air ratio, however, rapidly duces the size of the clinker ring and makes it more ongy and friable. At 200 lb per hr air rate, increasing steam-air ratio from 0.07 to 0.12 reduces the ight of the clinker ring from more than 10 lb to about 2¼ lb. Most of the tests were run at 0.12 steam-air ratio. At this value the weight of clinker ring did not exceed 4 lb except for the test at the highest air rate, and the gasification process appears to be unaffected by the ring in all these tests.

Increasing the blast rate increases the size and density of the clinker ring rapidly. Very roughly the weight of the clinker ring increases as the square of the blast rate.

The size of the clinker ring decreases and the position of the ring on the refractory wall is lowered slightly as the operating pressure is increased. Very approximately the ring decreases 0.7 lb per atmosphere of increased pressure at a 200 lb per hr air rate and 1.4 lb per atmosphere at 300 lb per hr air rate.

Bed Temperature

Increasing the steam-air ratio reduces the maximum bed temperature, displaces the point of maximum temperature upward slightly, and decreases the make-gas temperature slightly. This is shown in FIG. 3, which is a plot of the temperatures obtained 90 minutes after the start of the test.

Increasing the blast rate increases the maximum bed temperatures as well as the make-gas temperature, and displaces the point of maximum temperature upward. This is shown in FIG. 4. The change in make-gas temperature is approximately the amount that might be expected to occur as the effect of surface heat losses on such a small producer.

The measurements of bed temperature by sighting a pyrometer through a water-cooled probe onto the bed were not entirely successful in all the tests. Condensation of water on the sight glasses and other difficulties arose particularly at pressures above 3

TABLE III: SUMMARY OF RESULTS OF TESTS WITH COKE

Test No.	Pressure, atm	Air rate, lb per hr	Steam air ratio	Rate of gasification of coke, lb per hr	Average depth of bed, in.	Average make-gas temperature, deg F	Composition of make gas, percent					
							CO_2	O_2	CO	H_2	CH_4	N_2
14	1	99.0	0.117	19.7	35.2	—	4.9	2.9	20.9	7.6	0.5	63.2
17	1	101.0	0.115	19.3	37.2	463	7.3	1.7	21.7	9.3	0.3	59.7
11	1	201.6	0.046	37.6	34.8	—	6.2	1.0	22.7	7.2	0.0	62.9
6	1	197.2	0.080	33.1	34.8	—	8.2	1.1	19.2	6.3	0.2	65.0
10	1	199.8	0.108	34.4	34.5	—	8.5	1.0	19.5	7.4	0.3	63.3
16	1	198.7	0.118	37.6	37.0	1120	8.5	0.5	20.7	8.8	0.2	61.3
12	1	201.5	0.151	35.0	35.2	—	9.3	1.1	18.1	9.1	0.4	62.0
9	1	298.0	0.072	50.8	33.2	—	5.5	0.9	23.9	7.7	0.1	61.9
13	1	296.4	0.116	53.5	35.2	—	8.8	0.8	19.6	7.6	0.4	62.8
15	3	99.1	0.116	19.5	36.9	321	6.0	1.8	23.4	9.7	0.2	58.9
7	3	191.7	0.070	35.9	34.9	—	5.9	1.0	22.7	6.1	0.3	64.0
8	3	198.8	0.081	36.5	35.0	—	6.1	0.6	23.2	6.3	0.4	63.4
18	3	194.0	0.120	36.9	36.4	880	7.8	0.5	21.6	7.8	0.5	61.8
19	5	195.9	0.117	40.8	38.0	800	6.8	0.6	23.8	9.0	0.8	59.0
20	6	203.1	0.122	40.5	36.8	820	5.8	0.3	25.4	8.0	0.3	60.2
21	7	206.4	0.121	38.9	38.2	790	5.9	0.6	23.3	7.7	0.8	61.7
1-C	6	396.0	0.120	83.9	30.0	1155	4.2	0.0	27.4	9.9	0.0	58.2
2-C	6	496.0	0.120	107.6	26.0	1245	6.3	0.4	25.2	9.6	0.2	58.3
3-C	6	651.0	0.117	136.4	31.0	1351	6.3	0.6	24.8	10.1	0.0	58.2

* Calculated from gas analyses.

atmospheres. Fairly good measurements were obtained, however, for two tests at 3 atmospheres, one at 100 lb per hr and the other at 200 lb per hr air rate. These tests are plotted in Fig. 5 together with comparable tests at 1-atmosphere pressure. The maximum bed temperature is decreased and the point of maximum temperature is lowered toward the grate as the pressure is increased.

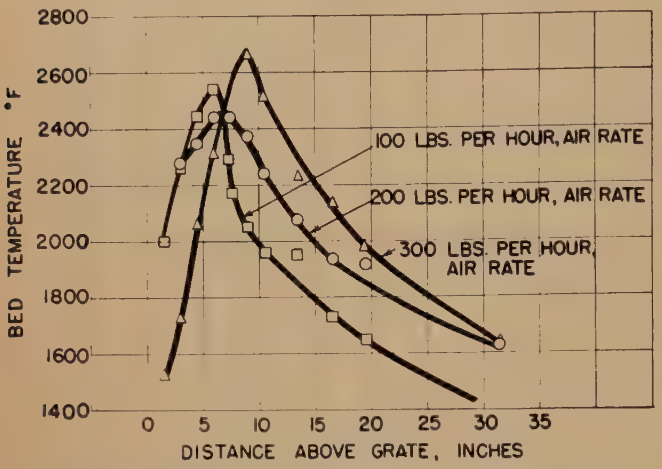


Fig. 4. Effect of blast rate on observed fuel-bed temperatures. Average test conditions: blast preheat, 200 F; pressure, 1 atmosphere; steam flow/air flow ratio, 0.12; fuel, high-temperature coke

Gas Quality

The gas composition was measured at the center of the bed, near the refractory wall, and in the off-take pipe. Fig. 6 shows the composition measured at these three locations for a typical test. As might be expected, the gas at the wall is of poorer quality than that at the center, although it apparently is not lean enough to explain entirely the lower quality of the make-gas in the off-take pipe. Perhaps further dilution occurs by a seepage of air from the refractory above the 35-in. level.

The extent to which the make-gas quality is reduced by the mixing of the wall gases with those from the center of the bed is a function of the size of the producer and the kind of a wall it has. The reduction is large in a small producer such as the developmental unit in which this test was made. The gas compositions at the bed center are, therefore, compared in order to give the basic effect on gas quality of varying the operating conditions. Unfortunately this cannot be done directly in all cases since no bed-center compositions were obtained during three of the tests at high rates and at 6 atmospheres.

Table IV shows the effect of steam-air ratio on gas quality. A threefold increase in steam-air ratio increases the hydrogen concentration about 40 percent and decreases the carbon monoxide concentration about 20 percent.

The effect of blast rate on gas quality is shown in Fig. 7. It is concluded from this, tentatively, that a five-fold increase in blast rate increases the CO concentration 25 percent and increases the H_2 concentration 14 percent. In Fig. 7, gas composition from
bed center is not available at the high-blast rates,
also the high rates are at 6 atmosphere and the co
parable low-rate points are at 1 atmosphere. As sho
later, the gas composition does not change with p
sure. Thus it is concluded that the change shown
Fig. 7 in the make-gas at the off-take is due principa
to the change in blast rate and also that it indicate
corresponding change in the gas in the center of
bed.

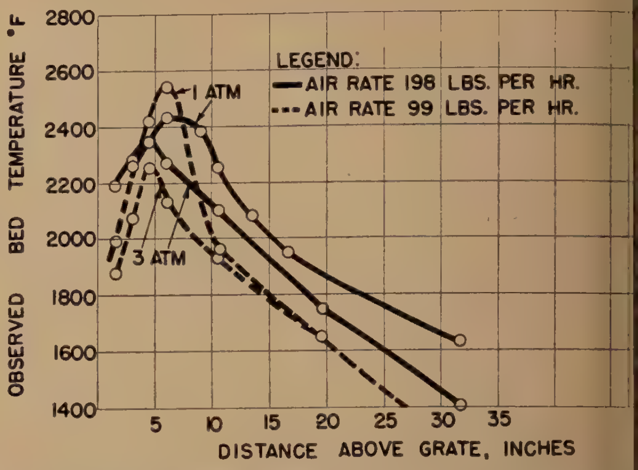


Fig. 5. Effect of operating pressure on fuel-bed temperatures. Average
conditions: blast preheat, 200 F; steam flow/air flow ratio, 0.12; fuel, h
temperature coke

Fig. 8 shows the effect of operating pressure on
quality. The data show that no appreciable change
composition occurs in going from one to 7 atmosphe

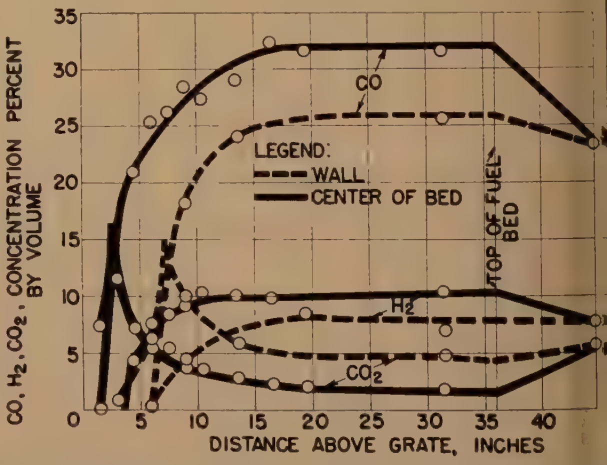


Fig. 6. Composition of gases in fuel bed at wall and at center of be
at various locations above the grate. Average test conditions: air rate
206 lb per hr; blast temperature, 220 F; steam flow/air flow ratio, 0.12
pressure, 7 atmospheres; fuel, high-temperature coke

Increased operating pressure might be expected
affect the gas quality adversely if the bed temperatur
are constant and if the following are the princip
reactions:

$$C + O_2 \rightleftarrows CO_2$$

$$C + CO_2 \rightleftarrows 2CO$$

$$C + H_2O \rightleftarrows CO + H_2$$

BLE IV: COMPOSITION OF GASES WITHIN THE FUEL BED FOR DIFFERENT STEAM-AIR RATIOS OF THE BLAST

Pressure, One Atmosphere

t Number	11		6		10		16		12	
rate, lb per hr	201.6		197.2		199.8		198.7		201.5	
am-air ratio	0.046		0.079		0.108		0.118		0.151	
el of sampling, in.*	19.5	31.5	19.5	31.5	19.5	31.5	19.5	31.5	19.5	31.5
s analyses, percent										
CO_2	0.7	0.5	2.7	2.2	2.6	2.3	3.9	2.9	5.6	4.4
O_2	0.9	0.5	0.2	0.4	0.4	0.4	0.5	1.2	1.0	1.0
CO	33.1	33.3	30.6	30.8	32.0	32.5	30.9	31.8	26.8	26.8
H_2	7.4	9.0	10.4	9.9	11.3	12.0	11.3	11.7	12.9	12.9
CH_4	0.4	0.2	0.2	0.6	0.2	0.2	0.5	0.3	0.3	0.3
N_2	57.5	56.5	55.9	56.1	53.5	52.6	52.9	52.1	53.4	54.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

* Distance above grate, center of fuel bed.

the same reaction temperature, pressure will have effect on Reaction (1), but an increase in pressure ld increase the concentration of CO_2 and H_2O in endothermic Reactions (2) and (3). An increase in tion temperature could counterbalance this lean-effect; but temperatures—at least at the bed center re lower at increased pressure as shown in FIG. 5. s state of affairs is not suitably explained. The e-gas quality in the off-take is found to improve ntly with increased pressure, which might lead to supposition that the wall temperatures and hence average bed temperatures might be increased with eased pressure. This is not borne out by the fact the make-gas temperature in the off-take decreased ntly with increased pressure.

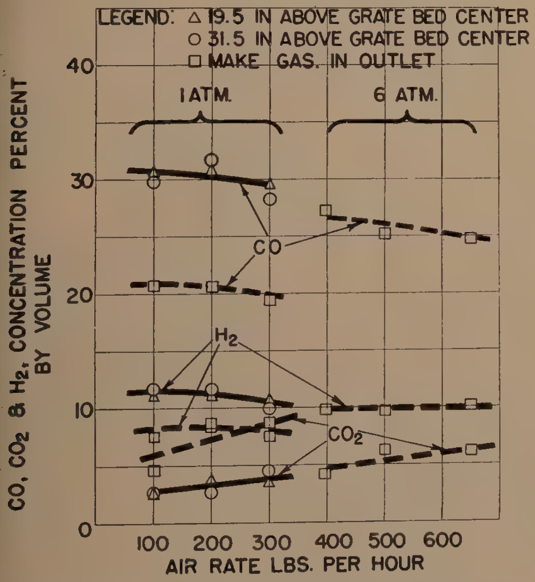


Fig. 7. Effect of blast rate on make-gas composition. Average test conditions: preheat, 200 F; steam flow/air flow ratio, 0.12; fuel, high-temperature coke

TESTS WITH BITUMINOUS COAL

itial tests of the gasification of bituminous coal ved the desirability of providing a system for the ection of carry-over which would overcome difficul- caused by the condensation of tar in the cyclones. qual importance was the need for a mechanically ated stirrer for agitation of the fuel in the "devolatilization zone" (top section of the fuel bed), to help to overcome channeling effects and the formation of coke masses impervious to the flow of gases. Accordingly, for tests with bituminous coal, major items added to the original producer were an efficient vortex separator, a combustor for the product gas, and a fuel-bed stirrer.

Modification in Equipment

FIG. 9 is a schematic drawing of the equipment used in gasification tests with bituminous coal. A water-cooled rake (*24*) with 3-in. long coke-breaker teeth, motor-driven through a variable-speed transmission is added to the original producer in place of the original bed-level indicator. A combustor (*9*) to burn the gas including the tar, and a cyclone separator (*10*) to collect the solids discharged from the combustor have also been added.

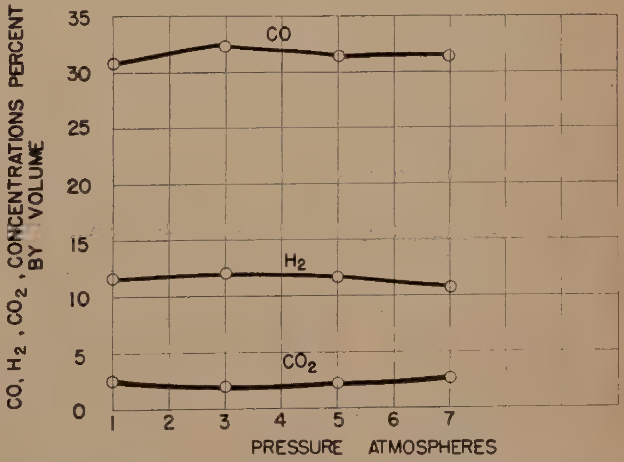
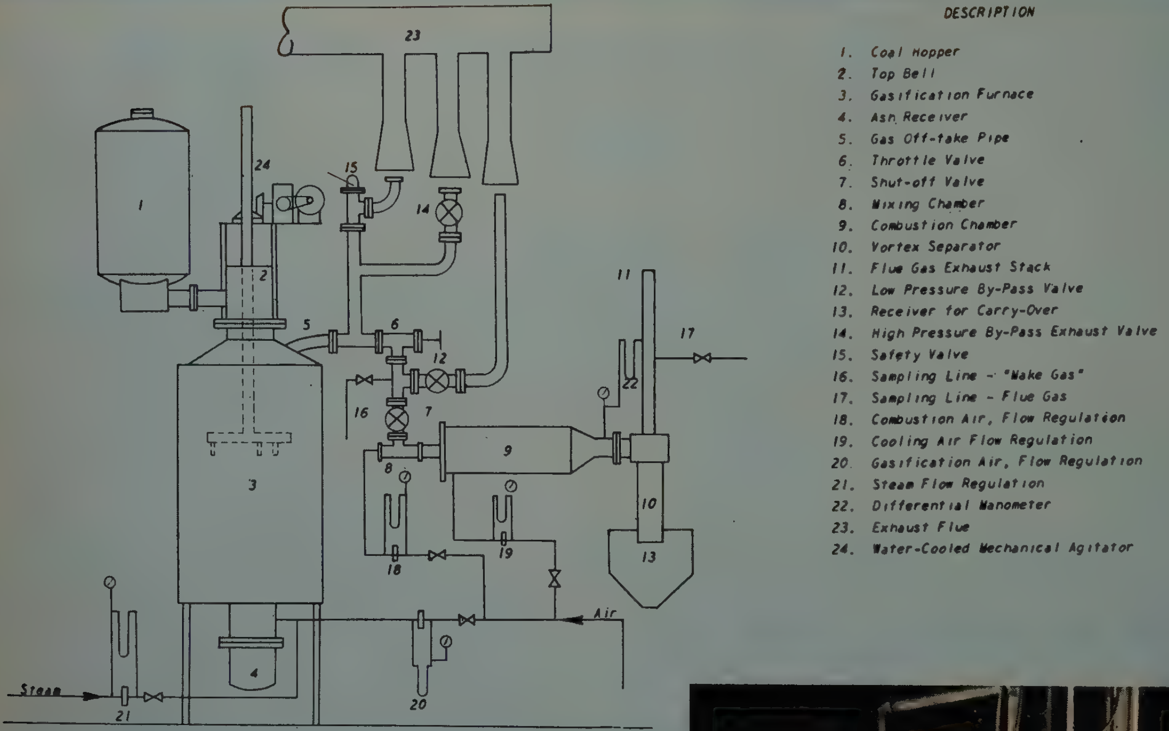


Fig. 8. Effect of operating pressure on gas composition at point in center of fuel bed located 31.5 in. above the grate. Average test conditions: air rate, 200 lb per hr; preheat, 200 F; steam flow/air flow ratio, 0.12; fuel, high-temperature coke

FIG. 10 shows the modified producer. The cylindrical gasification furnace appears in the central foreground, above which is the top bell and the drive mechanism for the fuel-bed stirrer. The pressurized coal hopper and coal delivery tube are shown in the upper left center. Only the end of the combustor can be seen at the left of the hopper. At the extreme left the vortex separator can be seen.

Method of Operation

During periods of carry-over collection, the gas, together with air for combustion, is admitted (FIG. 9) to the combustor (*9*), where it is burned. Cooling air (*19*) is admitted to the combustor to lower the temperature of the combustion gases before they enter the vortex separator (*10*). The solid carry-over material is removed from the gas stream and is deposited in the separator receiver (*13*). Flue gases are exhausted to the atmosphere. A series of 10-minute collection periods is established during each test.



23
24
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14
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10
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19
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Air
4
Steam
21
20
DESCRIPTION
1. Coal Hopper
2. Top Bell
3. Gasification Furnace
4. Ash Receiver
5. Gas Off-take Pipe
6. Throttle Valve
7. Shut-off Valve
8. Mixing Chamber
9. Combustion Chamber
10. Vortex Separator
11. Flue Gas Exhaust Stack
12. Low Pressure By-Pass Valve
13. Receiver for Carry-Over
14. High Pressure By-Pass Exhaust Valve
15. Safety Valve
16. Sampling Line - "Make Gas"
17. Sampling Line - Flue Gas
18. Combustion Air, Flow Regulation
19. Cooling Air Flow Regulation
20. Gasification Air, Flow Regulation
21. Steam Flow Regulation
22. Differential Manometer
23. Exhaust Flue
24. Water-Cooled Mechanical Agitator

Fig. 9. Schematic drawing of the gas producer and equipment modified for bituminous-coal carry-over tests

To begin a test, a small wood fire is started in the open generator by means of a gas torch inserted through the lowest sample port. All of the coke taken from the generator at the conclusion of the previous test is added to the wood fire, while air is supplied by the blower at a rate of about 180 lb per hr. If necessary, high-temperature coke is added at intervals until the fuel bed is about 35 in. deep. Sufficient steam is used to prevent the formation of clinker while the bed of coke is being ignited.

After the fuel bed and combustion are well established, the air and steam are shut off and the hopper and top bell are bolted into place. The desired rates of flow of air and steam and the generator pressure are then established. After the bed of coke has burned down to the desired thickness, the coal feed is started at a rate sufficient to maintain this depth of bed. As soon as the coal feed begins, the stirrer is started, and thereafter is run continuously. The grates are shaken every 10 minutes throughout the operation of the generator. About 1½ hr is required after the feed is started to attain steady-state conditions before carry-over tests are begun. During the 1½-hr stabiliza period, as well as between tests with combustor, ma gas is vented through the by-pass valve and burne

To start the combustor for a test run, the hydro pilot burner is first lighted by means of a spark p The combustion-air flow is set at the desired r

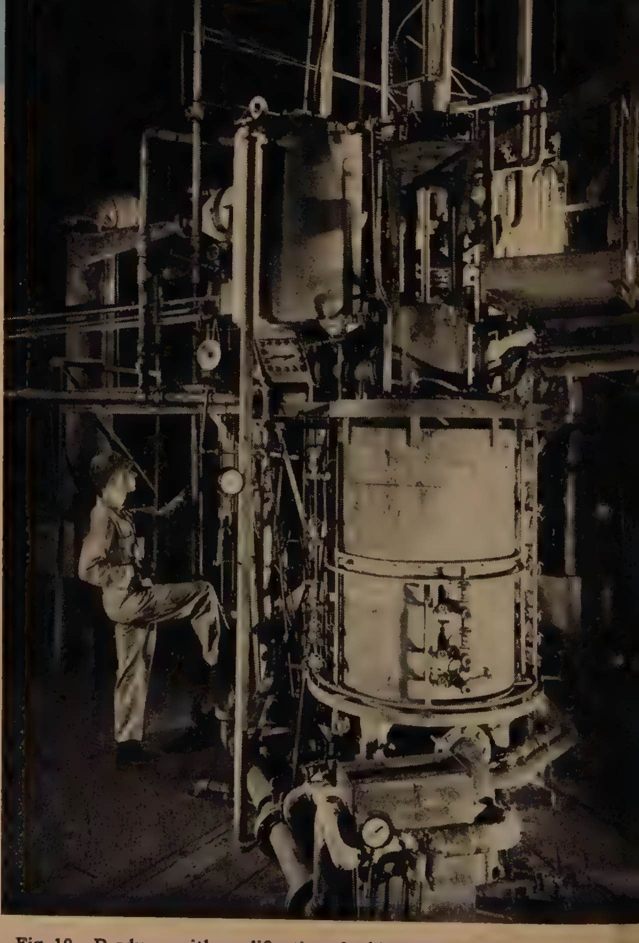

Fig. 10. Producer with modifications for bituminous-coal carry-over tests

ich is about 100 to 150 percent of that for the sification air. The combustor shut-off valve is then ened and the by-pass valve is closed. As soon as the s is burning well, the hydrogen pilot is turned off, d a few seconds are allowed for the combustor to rm up before cooling air is admitted. The flue-gas mperature is held between 1200 F and 1500 F. In utting off the combustor, the by-pass valve is opened fore the shut-off valve is closed.

Carry-over is collected only during operation of the mbustor. Samples of the make-gas are taken at e-minute intervals during periods for the collection carry-over; the flue gas is sampled over the entire riod of operation of the combustor.

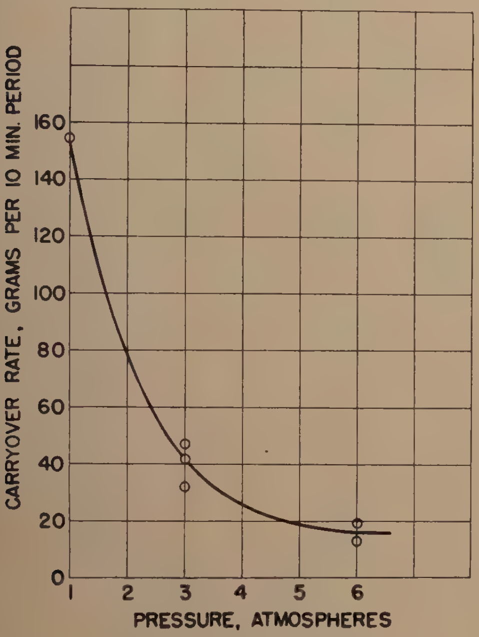

Fig. 11. Effect of operating pressure on carry-over rate. Average test conditions: air rate, 200 lb per hr; preheat, 215 F; steam flow/air flow ratio range, 0.10 to 0.12; fuel, Millers Creek coal

sults of Carry-over Determinations

One objective of the gasification tests with bitumi- us coal is to determine the carry-over, which is the e of transport of solid material in the gas carried over m the fuel bed. Every effort was made to maintain conditions of the fuel bed as uniform as possible oughout each test so that the over-all results would lect clearly the specific conditions under which the t was run. The combustor was placed ahead of the arator for the purpose of burning the tar in the gas, d making possible the separation of solid carry-over thout difficulties brought about by the condensation tar. It was made as short as possible to reduce to a nimum the burning of carbon in the solid particles. e values obtained are at least of the correct order magnitude for producers of this type, but it is ognized that the size and type of the producer can bstantially affect the carry-over. It is also recognized t the weights of carry-over should be corrected for devolatilization of particles of coal which would be ried in the gas stream, and for partial or complete burning of the very fine sizes of coal or coke in the combustor. It was not possible to make this correction, as the extent of devolatilization or burning of fine particles was not known. When analyzed, the carry-over material had much the same composition as would be expected if high-temperature coke had been made from the coal. However, it is probable that the tests furnish reasonably accurate values for the carry-over produced under varying conditions of operation.

Factors investigated during the course of some 30 carry-over tests included: operating pressure; size and type of coal; speed of rotation of the fuel-bed stirrer; operation with and without the coal feed during collection periods; and rates of gasification.

Table V gives data for the complete series of tests. The effects of the principal variables of the tests are summarized and discussed in the following:

Effect of Pressure

Operation under pressure was found to be a major factor in reducing the carry-over of solids from the producer. To evaluate this effect, a series of tests was run with the relatively free-burning Millers Creek coal at an air rate of 200 lb per hr, and at pressures of one, three, and six atmospheres. Fig. 11, in which values of carry-over rates are plotted against the pressure in atmospheres, shows the resulting relationship. With the operating rate and steam-air ratio held constant, there is a decrease in the weight of carry-over as the pressure is increased and as the gas velocities are correspondingly decreased.

Effect of Gasification Rate

A number of tests were run under comparable conditions except that the rate of gasification was varied. These tests were run at six atmospheres pressure with coals from the Millers Creek and Ohio No. 8 beds. For all but two of the tests, stirrer and feed mechanism were in operation during periods of carry-over collection.

Fig. 12 shows the effect of air rate on carry-over rate for tests in which the air rate was varied over a range

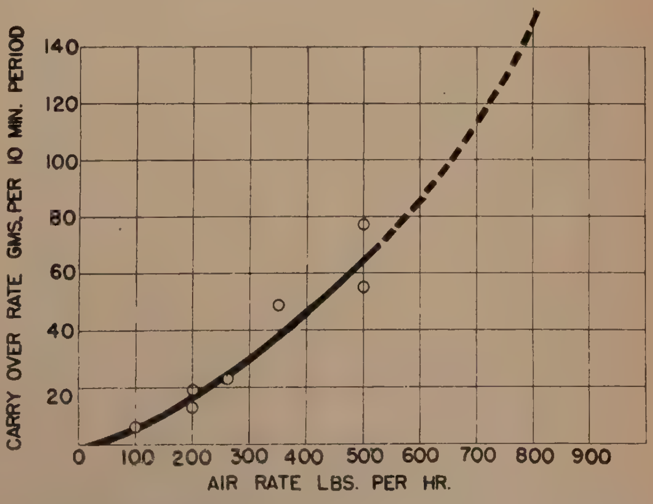

Fig. 12. Effect of blast rate on carry-over rate. Average test conditions: preheat, 215 F; steam flow/air flow ratio range, 0.10 to 0.12; pressure, 6 atmospheres; fuel, Millers Creek coal

TABLE V: SUMMARY OF RESULTS OF CARRY-OVER MEASUREMENT

Test No.	Gasification air, lb/hr	Feed source	Feed On or Off	Stirrer* On or Off	Carry-over, grams per 10-min period							Carry-over percent through 100 mesh
					1st	2d	3d	4th	5th	6th	Avg	
				Pressure, One Atmosphere								
3-B	202	Millers Crk	Off	On	222.5	118.5	69.0				136.6	‡
8-B	194	Millers Crk	On	On	155.6	151.3	180.4	134.3	151.4		154.6	60.5
11-B	199	Millers Crk	Off	Off	15.6	24.7	31.4	42.1			28.5	44.2
12-B	198	Millers Crk	On	On (2.1 rpm)	219.4	167.9	269.2	184.4	182.0	185.8	201.8	51.7
13-B	198	Millers Crk†	On	On	185.0	164.5	184.1	181.3			178.7	52.3
14-B	198	Hi-Temp Coke	On	On	....	94.7	86.7	87.0	92.1		90.1	47.0
15-B	200	Ohio No. 8	On	On	168.7	203.2	126.5	140.1	126.5		155.0	53.0
				Pressure, Three Atmospheres								
4-B	240	Millers Crk	On	On		17.2		65.6			41.4	92.7
			Off	On	135.5		124.5		134.7		131.6	96.1
5-B	198	Millers Crk	On	On	8.5		13.9		75.0		32.5	92.8
			Off	On		71.7		228.4		117.1	139.1	86.7
6-B	197	Millers Crk	On	On	29.0	45.7	54.2	48.5	60.3		47.5	94.9
				Pressure, Six Atmospheres								
7-B	199	Millers Crk	On	On	14.1	6.3	43.4	14.0	10.1	28.0	19.3	92.0
9-B	101	Millers Crk	On	On	2.5	18.9	0.7	4.7			6.7	‡
10-B	256	Millers Crk	On	On	71.7	69.9	104.8				82.1	97.5
16-B	197	Millers Crk	Off	Off		8.7	3.1	2.8	1.6		4.1	59.9
17-B	197	Millers Crk	Off	Off	2.6	1.2	2.4	2.9	1.8		2.2	50.7
19-B	200	Millers Crk	On	On	7.4	8.4	14.3	20.0	7.4	16.1	12.3	87.9
20-B	260	Millers Crk	On	On	44.9	19.8	18.7	12.3			23.9	94.6
21-B	260	Millers Crk	On	On	15.4	5.5	2.9	23.1			11.7	79.1
22-B	259	Ohio No. 8	On	On	35.1	23.7	37.6	30.8	44.8	15.8	31.6	89.4
4-C	350	Millers Crk	On	On	53.0	43.1	50.3	51.3			49.4	95.7
5-C	501	Millers Crk	On	On	77.3	100.8	68.1	64.0			77.6	96.8
6-C	502	Millers Crk	On	On (2.1 rpm)	208.0	175.1	220.1	278.0			220.3	93.7
7-C	500	Millers Crk	On	On	82.1	37.4	61.1	50.6	44.2		55.1	96.3
9-C	352	Ohio No. 8	On	On	46.6	77.3	89.9	112.6	66.6	53.0	74.3	96.8
10-C	499	Ohio No. 8	On	On	99.8	91.3	86.7	163.0	164.1		121.0	96.1
12-C	501	Ohio No. 8	On	On§	113.2	132.1	135.8	103.7			121.2	96.7

* Normal speed of stirrer, 0.6 rpm.
† This coal ⅜ × 0 in.; all others ¾ × ⅜ in.
‡ Not determined.
§ Stirrer teeth lengthened from 3 in. to 6½ in.

of 100 to 500 lb per hr while the pressure was held at six atmospheres. The result is a slowly rising curve which indicates that the weight of carry-over becomes progressively higher as the rate of gasification is increased, and that the relationship is not linear.

The curve is projected to reach the maximum value of carry-over shown in Fig. 11 (namely, 155 grams per 10-min period at 200 lb per hr and one atmosphere). It shows that the same carry-over is obtained at six atmospheres at four times the air rate as that obtained at one atmosphere. This indicates that the carry-over is not proportional to air rate and inversely proportional to pressure. Thus, if a given value for carry-over is not to be exceeded, the rate of gasification cannot be increased in proportion to the pressure, but must be held to some lower value. Information based on work with the Lurgi gasification unit in Germany for a range of pressures up to 25 atmospheres, and based on theoretical calculations at various pressures, temperatures, and particle sizes, indicates that the carry-over varies approximately inversely as the square root of the pressure.⁽¹⁾

Fig. 13 shows a plot of carry-over rate against velocity of the gas above the fuel bed. The velocity is based upon the actual volume rate of the gases above th bed and the cross-sectional area of the retort. Th results of comparable tests with coke are included.

The curve indicates that the carry-over is relate to the nature and properties of the fuel in use. possible explanation for the higher carry-over loss with coke may lie in the absence of a top layer of sem plastic material such as would be present at the to of the bed when caking coals are gasified. This poss bility, however, does not explain why the carry-ov from a fuel bed of Ohio No. 8 coal, which is strong caking, is somewhat greater than for the more weak caking Millers Creek coal. However, since the carr over measured for the tests with coal consists of mat rial almost completely devolatilized, a correction shoul be made for the weight of volatile matter in the carr over before it enters the combustor. If this factor we known and applied, the lines representing the resul of tests with coal might more nearly approach that the results with coke.

Effect of Stirrer Motion

Study of the results of all the determinations carry-over, a few of which were run without the u of the fuel-bed stirrer, leads to the conclusion that th

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(1) Private communication, Dr. Wilhelm Gumz, consultant, Battelle Memorial Institute.

ovement of the stirrer in the top section of the fuel ed is a major factor in the production of carry-over. threefold increase in the speed of the stirrer, from normal rate of 0.6 rpm to 2.1 rpm, raised the carry-ver by only 30 percent for tests with Millers Creek al at one atmosphere and an air rate of 200 lb per ; however, for comparative tests of the same coal six atmospheres and an air rate of 500 lb per hr, e carry-over was increased by approximately 300 ercent.

The action of the stirrer probably results in forced rasion of pieces of the relatively friable low-tem-erature coke in the distillation zone of the fuel bed. he resulting fine material can then be carried up-ard from the bed of gases. An agitator of some type, wever, appears to be necessary for operation of an erfeed gas producer with bituminous coals.

fect of Coal Feed Interruption

Initially it was believed that the stream of combus-on gases rising from the fuel bed of the producer ould entrain an appreciable amount of the fine sizes coal being dropped onto the bed from above. The sults of several tests with the coal feed shut off ring periods of carry-over collection, although some-hat inconclusive, indicate that the carry-over from is source is considerably less than expected.

In this regard, the weights of carry-over obtained Tests 4-B and 5-B (Table V) should be noted. For ese tests, the stirrer was in operation continuously, it alternate collections were made with and without al being fed. For both tests, the weight of carry-over aterial collected during periods when coal was being d was far less than that collected during periods nen the feed of fresh fuel was stopped. This might be plained by assuming that when the coal feed is ut off, the fresh fuel is rapidly coked, and the pro-ction of fine material by abrasion resulting from e motion of the stirrer is increased. When the feeding coal is stopped, there is no longer the layer of semi-astic material which may act as a filter for the par-les, and carry-over is increased.

As might be expected, the amount of carry-over oduced was lowest during operation with both feed d agitator turned off. At a pressure of six atmos-eres, only a few grams were removed from the gas ring 10-min collection periods. These results are incipally of academic interest, however, inasmuch a producer could not be operated for long under ch conditions.

aracteristics of the Carry-over

The carry-over was a fine, dry, black, carbonaceous aterial. From determinations of ash content, it peared that very little of the solid carry-over had en burned in the combustor.

Except for tests without operation of the agitator d coal feed, the average size of the particles of carry-er was appreciably smaller at the higher pressures. is was true for material passing a 200-mesh screen as well as that passing a 100-mesh screen. For all tests at one atmosphere pressure, average percentage of material passing a 100-mesh screen was 51.4 percent; for three atmospheres pressure, the average value was 92.6 percent and for a pressure of six atmospheres, 90.0 percent. The lower gas velocity at the higher pressures is a major factor in accounting for the differences in size of the carry-over particles.

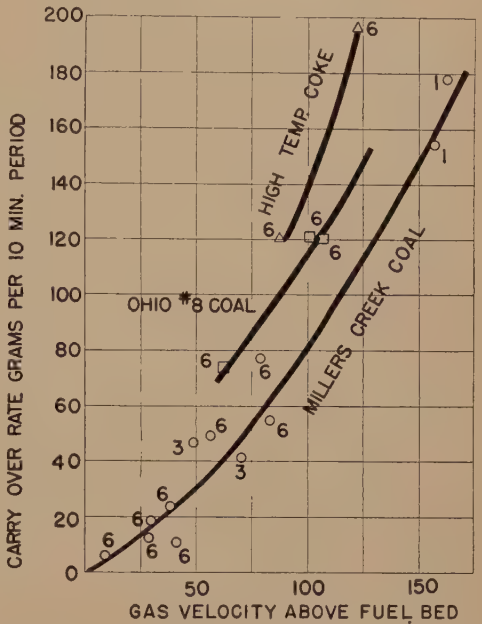

Fig. 13. Effect of velocity of gases above fuel bed on carry-over rate. Note: number located at side of point is pressure of test in atmospheres. Average preheat temperature, 215 F

It was evident that the tar had been completely burned with the gas in the combustor, as the carry-over material exhibited no trace of tarry material.

Caking and Clinkering with Low-ash Coals

At the higher gasification rates in particular, there was a pronounced tendency for the top part of the fuel to become bridged with a solid mass of coke, thus requiring the test to be stopped. These difficulties were overcome to a satisfactory degree for tests with Millers Creek coal at air rates up to 250 lb per hr after installing the stirring mechanism; but, at rates of 350 and 500 lb per hr, caking still remained a problem of operation. Further progress was made in controlling caking by operating with a shallower fuel bed and by close control of the rate of coal feed.

The caking was greater when the more strongly caking Ohio No. 8 coal was used. In an attempt to alleviate the problem, the teeth on the stirrer were lengthened from three inches to 6½ in. A test at the 350-lb air rate after making this modification resulted in improved fuel-bed conditions. At a 500-lb air rate, less improvement was apparent; and after about two hours of operation the test was stopped when a bridge of coke was formed in the upper section of the producer above the arm of the stirrer. Operation at an air rate of 500 lb per hr corresponds to a rate of gasification of about 140 lb of coal per hr, which is far above the range of operation in commercial gas-producer practice.

An attempt to run a test with Millers Creek coal at an air rate of 650 lb per hr was unsuccessful. The temperature of the gas became very high (about 1550 F) and the off-take pipe and throttle valve became visibly over-heated, making it inadvisable to continue the test under pressure. No attempt was made to run another test at this air rate.

Except in one test (No. 5-C), no difficulty due to clinker formed during the test periods, as measured by the effect of the clinker collection on either the coal gasification rate or on the quality of the gas, was encountered. In this test at an air rate of 501 lb per hour the clinker formation was severe enough to cause a small progressive decrease in the quality of the gas. At the end of all the tests (Table V) there was a ring of clinker stuck to the refractory wall, about two inches vertically along the wall and projecting one inch radially inward. It should be noted also that in addition to lasting only about three hours, all of the tests were made on rather low-ash coals (3 to 8 percent) and with the steam-air ratio held between 0.09 and 0.12.

Effect of Steam-air Ratios on Clinker Formation and on Gas Composition with High-ash Coals

In commercial gas-producer practice, steam is added to the air blast primarily to control the formation of clinker. A further effect of introducing steam is to increase the hydrogen and carbon monoxide of the gas without a corresponding increase in diluent nitrogen. Hence, up to an optimum steam-air ratio, the quality of the gas is improved. As the steam content of the blast is increased beyond the optimum value, however, the lowered temperature in the fuel bed slows the reduction of carbon dioxide by carbon, and the steam reacts with carbon to form CO_2 and H_2 rather than CO and H_2, with a resultant net decrease in heating value of the gas. In commercial practice, the addition of steam is regulated to achieve a balance between the rate of gasification, clinker formation, and coal properties—chiefly the ash content and ash-fusion properties of the coal.

The effect of an increase in the steam-air ratio above values of 0.10 on make-gas composition and on clinker formation was determined in a series of tests in the refractory-lined producer with the Pittsburgh coal. FIG. 14 shows the effect of steam-air ratio on the composition of the producer make-gas at 6 atmospheres and 250 lb per hr air rate. The ratio of CO to CO_2 is lowered and the hydrogen is increased as the steam-air ratio is increased. For purposes of comparison, the results of two runs with coal from the Illinois No. 5 bed are also plotted as dotted lines. Although data at only two steam-air ratios were available for the latter, the trend in changing gas composition closely follows the results with the Pittsburgh coal.

A test run with coal from the Pittsburgh bed at an air rate of 350 lb per hr and a steam-air ratio of 0.12 resulted in severe clinkering conditions in the fuel bed. At a lower air rate of 250 lb per hr, and with the stea air ratio increased to 0.36, the rate of clinker formati was lowered and, a more friable clinker was forme For two tests run at steam-air ratio of 0.36, the tot weights of +¾-in. and larger clinker formed at t end of three hours of operation were 11.0 and 8.5 l respectively. An equivalent run at a steam-air ratio 0.18 formed 17.0 lb. This represents a substantial r duction in the total amount of clinker; but, unfort nately, much of the clinker was in the form of a ring slag which was firmly attached to the refractory linin thus precluding operation for periods longer than abo three hours. Similar tests run with the special lot high-ash Illinois coal gave similar results, although th clinker was more friable and more porous than tha from the Pittsburgh coal.

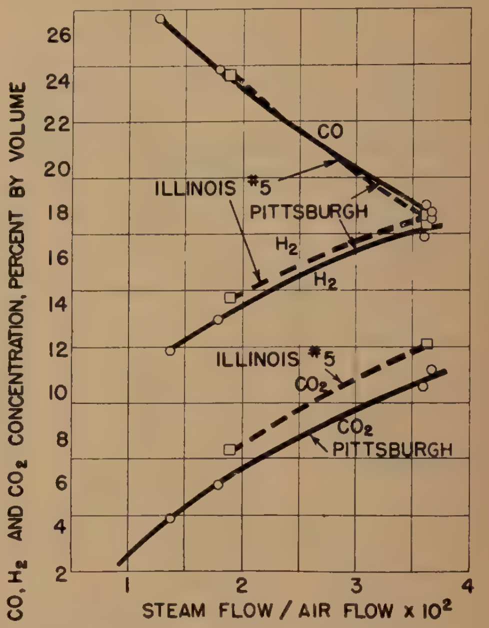

Fig. 14. Effect of steam flow/air flow ratio on make-gas composition. Average preheat, 215 F

In an attempt to alleviate the clinker condition, series of ports was built into the wall of the produc below the point where the ring of clinker usually forme The purpose of this construction was to attempt t prevent the fusion of clinker to the lining by the in troduction of a flow of steam upward along the pro ducer wall. The attempt was unsuccessful; little if an change was noted compared with previous tests with out the added steam ports.

The Effect of Preheating the Air Blast on Gasification

The combustion air of a gas-turbine plant, availab also to the producer, will have a temperature lying i the range of 400 F to 800 F. Hence, to fit the gas-turbin application, the air blast should be preheated t temperatures in this neighborhood. Furthermore, hig preheat temperatures might have other advantage since fuel-bed temperatures would be increased and us of higher steam-air ratios would increase the quality c the gas. Therefore, some of the tests were made t termine the effect on producer operations of pre- ating the blast to relatively high temperatures.

For these tests the gas-fired tubular preheater ginally provided to heat the steam-air blast to the quired saturation temperature was inadequate to rnish high preheats, so a direct-fired preheater using drogen as a fuel was added ahead of the producer. e of hydrogen as a fuel added water vapor to the stream, which was taken into account in adjusting e total rate of steam addition. During initial tests, e rate of flow of air was increased by the stoichio- etric quantity of air required to burn the hydrogen. ecause this practice led to a slight reduction in the ygen-nitrogen ratio of the primary air supply, it was er revised, and oxygen in stoichiometric quantities as added to the system before burning the hydrogen. though comparison of the results of tests by both ethods showed no change in rate of gasification or s quality, the practice of adding oxygen and hydrogen as continued for subsequent tests.

The preheat tests were run in a refractory-lined nerator equipped with manually operated finger ates. With manual operation it is difficult to main- in a balance between the rate of ash removal and e rate of ash release in the bed. If the rate of re- oval is too slow, the increase in concentration of ash rnishes conditions favorable for the formation of nker; if too rapid, the loss of carbon in the refuse is cessive. With use of a mechanical system for ash moval, the removal of ash can be accomplished in more uniform manner. However, for purposes of termining relative effects and trends due to increasing eheat, the results obtained with the manually oper- ed grates are considered adequate.

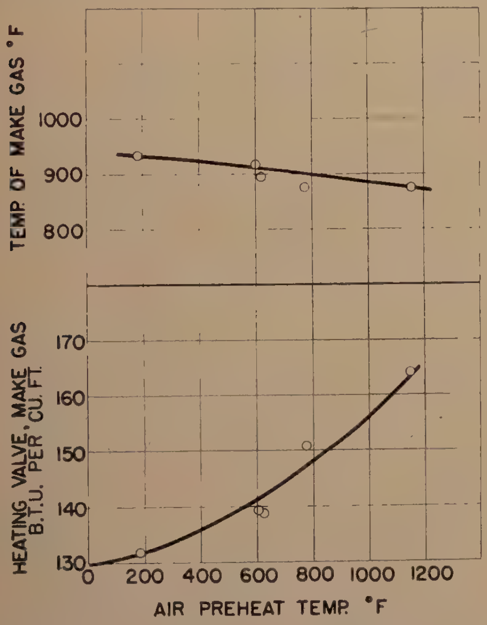

Fig. 15(*a*). Effect of blast preheat on heating value and temperature of make-gas. Average test conditions: air rate, 250 lb per hr; steam flow/air flow ratio, 0.34; pressure, 1 atmosphere; fuel, Illinois No. 5 coal

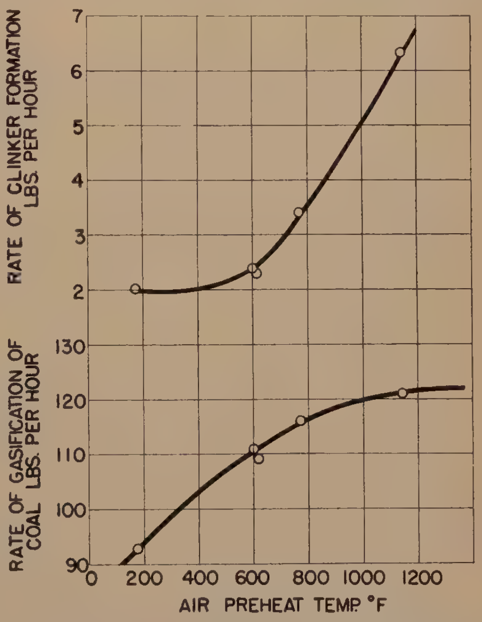

Fig. 15(*b*). Effect of blast preheat on coal gasification rate and clinker formation. Average test conditions: air rate, 250 lb per hr; steam flow/air flow ratio, 0.34; pressure, 1 atmosphere; fuel, Illinois No. 5 coal

FIG. 15(*a*) and 15(*b*) show the effect of increased eheat temperatures on the gasification of coal from the Illinois No. 5 bed. All tests were run at a pressure of one atmosphere, an air rate of 250 lb per hr, and a steam-air ratio of 0.34. The weight of clinker formed is based on particles ¾ in. in size and larger.

On the basis of the test results shown in FIG. 15(*a*) and 15(*b*), the following general conclusions with regard to the effect of preheat are drawn:

(1). The heating value of the make-gas is increased. The lower curve in FIG. 15(*a*) shows this trend. Plots (not shown) of the CO/CO_2 ratio and percentages of CO and H_2 show a similar upward trend with increasing blast temperatures.

Work reported in the literature demonstrates that preheating the blast so increases the rate of reaction that oxygen disappears at a lower depth in the fuel bed, and the percentage of carbon monoxide in the gases is higher for the same depth of bed. P. Nicholls,(2) who studied overfeed fuel beds, has shown this to be true. He also has shown that some of the preheat is used up in the endothermic reaction of converting carbon dioxide to carbon monoxide, and that some of the preheat appears as a higher temperature of the combustion gases. It is to be noted that the results of the present work do not show an increase in gas temperature as the temperature of preheat is raised; in fact, a slight decrease was noted for fuel beds about 20 in. deep, as shown in the curve at the top of FIG. 15(*a*). This may be ascribed to the narrowing of the oxidation zone to the additional exothermic reactions occasioned by the substantial amounts of steam in the air blast, and, in a minor way, to increased radiation losses from the fuel-bed section of the generator. Wheeler(3) has reported that one effect of preheat is to lower the temperature of the make-gas.

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(2) "Underfeed Combustion, Effect of Preheat, and Distribution of Ash in Fuel Beds," *Nicholls, P.*, U. S. Bureau of Mines, Bulletin 378, 1934, pp. 6–10.

(3) "Producer Gas and Producer-Gas Practice," by Wheeler, R. V., *Fuel in Science and Practice*, Vol. 2, p. 295 (1923).

(2). The rate of gasification is increased. The curve at the bottom of FIG. 15(*b*) shows the increase in gasification rates as the temperature of preheat is raised.

(3). The formation of clinker is increased. The top curve in FIG. 15(*b*) shows that the total weight of clinker increases very rapidly with preheat temperature. Although the steam-air ratio was held constant for these tests, since the temperature in the oxidation zone increases with preheat, additional steam might have been used to advantage to cool the bed and prevent clinker. The coal used in these tests was purposely selected to have a relatively low ash-softening temperature, 2000 F, and a high ash content, which makes its use difficult from a clinkering standpoint.

Additional tests were run with coal from Millers Creek bed to check the effect of air preheat up to temperatures of 750 F. In general, the trends were similar to those obtained with Illinois coal, except that the rate of clinker formation did not change appreciably from an average value of about one pound per hour over the range of preheat temperatures employed. The low ash content of the Millers Creek coal (3.5 percent, as compared to 18.5 percent for the Illinois No. 5 coal) may largely account for the lower rate of clinker formation. The ash-softening temperatures are about the same.

Although further study of the relation between clinker formation, steam addition, and preheat temperature would have been of interest, these variables were not investigated further.

Producer Response to Rapid Load Changes

A gas producer applied to a gas turbine as well as to several other industrial devices is subject to rapid changes in load. To explore the capability of a producer in this respect, several tests were run. During one of these the air rate was abruptly changed from 150 lb per hr to 500 lb per hr. Coal from the Millers Creek bed was used, and the producer was operated at six atmospheres.

The procedure for the test was as follows: the fuel bed was stabilized for a period of 70 min at a depth of about 18 in., using an air rate of 155 lb per hr and a steam-air ratio of 0.10. The air rate was then raised to 500 lb per hr; manipulation of the valves for this change required about five seconds. The rates of coal feed and steam admission were increased to appropriate values at the higher air rate as soon as possible after the air rate was changed. Sampling of the make-gas was started immediately after the increase in air rate. Thirteen samples were taken at 20-sec intervals over a period of four minutes. A recording potentiometer was used to obtain a continuous record of the make-gas temperature.

The foregoing procedure was repeated later in the run after operation for a period of 20 min at the lower air rate while gas-sampling equipment was being changed. The same procedure was followed during the second phase of the test, except that eleven samples were taken over a period of three minutes.

FIG. 16 is a plot of the make-gas temperature and carbon dioxide and carbon monoxide concentratio during the course of the test. The abrupt change in rate led to an almost instantaneous increase in the g temperature. The higher temperature was held, wi some variation, over the period of the higher air ra With change to the lower air rate, the temperatu dropped to the lower level, though not as rapidly as

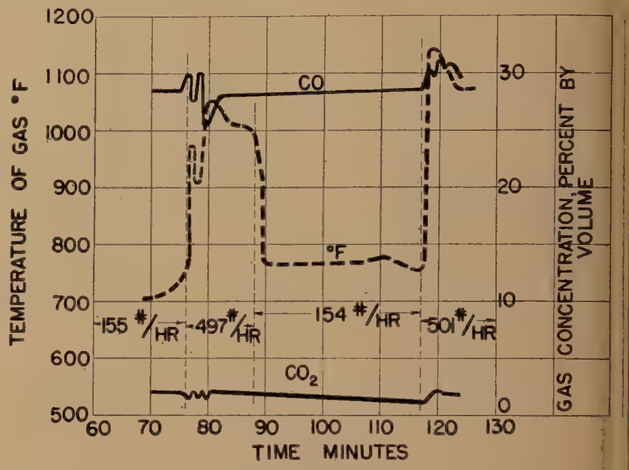


Fig. 16. Effect of rapid variation in air-rate on make-gas composition and temperature. Average pressure, 1 atmosphere; fuel, Millers Creek coal

had risen after increasing the air rate. During t interim period at the lower air rate, the temperatu of the gas was stabilized at a slightly higher leve When the air rate was increased for the second tim the gas temperature again increased very rapidly.

Samples of the gas taken during the period of rap changeover and throughout operation at both air rat were substantially constant in composition over t period of the test. Some variation is evident during t period when samples were being taken at 20-sec inte vals following the change in air rate. This may caused by a combination of factors inherent in t establishment of new equilibrium conditions in the be involving the rate of coal feed, steam-air ratio and be depth.

Results of the test, in general, may be summarize as follows: (1) abrupt increase in air rate is followe closely by establishment of a new temperature level f the gas; (2) minor variations in gas concentrations an heating values occur with the rapid change in air rat but, in general, the gas composition is substantially u changed; and, (3) in view of the foregoing, it may expected that the producer will follow changes in loa to an acceptable degree. These conclusions are base on the assumption that satisfactory fuel-bed condition can be maintained over the range of air rates involve particularly with respect to caking and clinkering co ditions.

Use of Water-cooled Generator Wall for Slag Control an Its Effect on Gasification Results

The adherence of clinker and slag to the refractor wall of the generator was a recurring problem durin the test program, particularly during operation at hig

: rates and with preheated air blast. Because of this, e refractory-lined shell was replaced with a water- oled section having the same effective inside diameter. G. 17 shows the essential features of the modification, hich was designed for operation at atmospheric essure.

Because of the relatively large ratio of retort-wall ea to cross-sectional area, the heat absorbed by the oling water was appreciable, approximately eight to n percent of the total heat input at 250 lb per hr ast rates. For a larger producer, the percentage heat ss would be substantially smaller.

The type of clinker formed during tests of the water- oled unit differed from that formed in the refractory- ned generator under comparable conditions. The slag clinker did not adhere to the steel wall, although the nount and size of the clinkers formed in the bed was ot greatly reduced except at the lower air rates. FIG. 8 shows a comparison of the results of tests in the ater-cooled and the refractory-lined generators. Both ries of tests were run with the special lot of high-ash al from the Illinois No. 5 bed, at air rates of 250 lb er hr, with a steam-air ratio of 0.34, and at atmos- heric pressure. The range of preheat temperatures nployed was from 200 to 1150 F.

The upper set of curves in FIG. 18 shows how the te of clinker formation increases with increase in pre- eat temperatures for the two types of walls. It would ppear that the effect of the water-cooled wall in cooling e fuel bed and in reducing slag formation is more pro- unced at the lower preheats, and results in a lower te of clinker formation. At the highest degree of pre- at, 1150 F, the rates of clinker formation for the two ries are identical. Of further interest in this regard, though not included in the curves given in FIG. 18, e the results of another series of preheat tests in the ater-cooled generator at a steam-air ratio of 0.18 stead of 0.34, other conditions being similar. A curve otting the rate of clinker formation for these tests ows the same upward trend, but is displaced up- rdly. These curves indicate that, as would be expected, the steam-air ratio is the ruling factor in clinker formation, and that the effect of the water-cooled surface extends only a relatively short distance radially into the fuel bed. The water-cooled surface is entirely effective in preventing adherence of slag to the wall, however, and is of practical value in that regard.

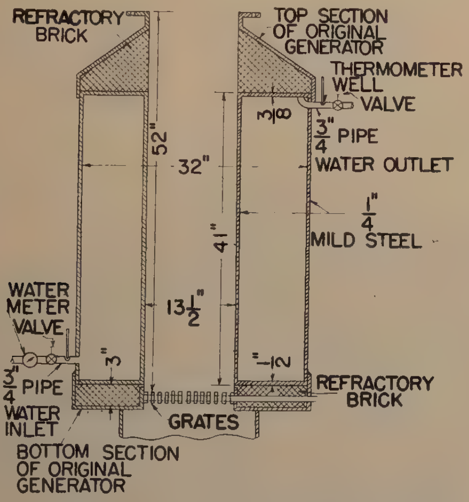


Fig. 17. Cross-section sketch of producer, showing water-cooled walls

The middle curves show that water-cooled walls gave no increase in the gasification rate with increase in preheat temperature, whereas refractory-lined walls show a trend to higher rates with increased preheat. The supplementary series of tests mentioned in the preceding paragraph, at a steam-air ratio of 0.18, show a small but definite trend to higher gasification rates as the degree of preheat is increased.

The lower curves in FIG. 18 show that, with both the water-cooled and the refractory-lined wall, the heating value of the product gas is increased with increase in preheat. The curve representing tests with the water-cooled unit falls off at the highest preheat temperature, but the trend with both systems is upward.

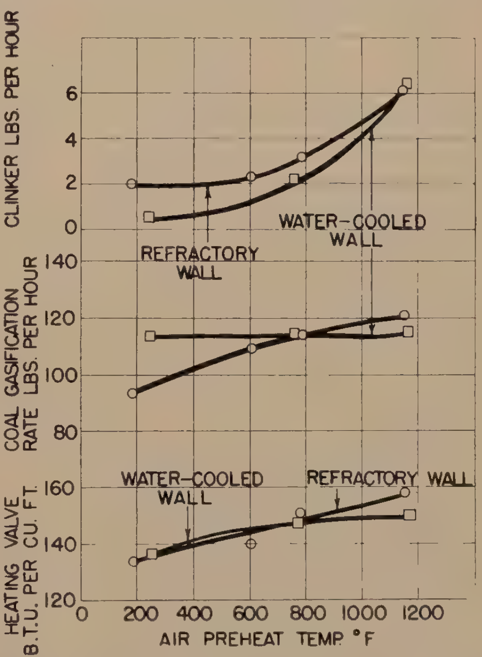


Fig. 18. Effect of blast preheat on gas heating value, coal gasification rate, and clinker formation. Average test conditions: air rate, 250 lb per hr; steam flow/air flow ratio, 0.34; pressure, 1 atmosphere; fuel, Illinois No. 5 coal

SUMMARY

The tests indicate that a satisfactory overfeed bituminous-coal gas producer can be made to supply fuel to a gas turbine. Rates of coal gasification of 100 to 200 lb per hr per sq ft of grate area can probably be achieved, resulting in a reasonably small producer. The carry-over of solid carbonaceous material in the gas at these rates and at pressures in the neighborhood of 6 atmospheres will be acceptable but will be of such a character and amount that separators will be required. The gas stream from which separation is required, however, is a fairly small portion of the total flow of the gas turbine plant. The gas stream is reducing and will not, therefore, allow separator fires to occur. Thus, the separator problem is not unreasonably difficult. The response of the producer to rapid load changes is satisfactory. Only the air rate must change substantially in synchronism with the load. The coal feed, the steam addition to the blast, and the ash removal rate can follow the load changes with time lags in the order of minutes. The necessary control equipment is simplified by these producer characteristics.

Additional tests could be run profitably in this small producer to explore the tar condensation problems, and to try out a clinker-grinding variable-speed grate. The problems then remaining should be worked out by means of tests on a full-scale producer.

The tests have indicated that the following features will be required of the producer:

(1). A water-cooled wall at least at the oxidation zone to prevent excessive deposit of slag on the retort wall

(2). A substantial coke breaker and stirrer in the top of the fuel bed to prevent fuel stoppage due to arching of the plastic mass and the coke

(3). A clinker-grinding variable-speed grate with proper control to prevent accumulation of clinker with variable load and with variable ash content of the coal.

Tests have not yet been run to define sufficiently the features required to avoid tar condensation and plugging due to mixtures of tars and solids. Such te should be run, but it is expected that the make-g temperature can be maintained high enough to ke the tar in a dry vapor form and still allow a sufficient wide range of load to be covered.

Gasification under the pressures required by a g turbine has no detrimental effect on the gas quali and has a beneficial influence on the carryover. It w require, however, the use of coal- and ash-handli mechanisms with the necessary pressure locks to pre surize the coal stream and depressurize the ash strea The tests described did not bear on the design proble of such machinery but it is expected that the proble in this design will be no more difficult than those in t design of the producer itself.

Acknowledgment

As is often the case, a number of people besides t authors contributed to this project, including Walt F. Robinson, Philip F. Kurz, Robert P. Miller, Willia C. Holton, and Herbert A. Kouns of Battelle Memor Institute, who operated the producer and took t data. Glenn B. Warren, Manager, Turbine Divisio General Electric Co., contributed a great deal both ideas and encouragement. Others whose contributio the authors wish to acknowledge, are Ralph A. She man and Wilhelm Gumz of Battelle Memorial Ins tute, and Anthony J. Nerad, Arthur H. Morey, a Ernest L. Robinson of the General Electric Co.

HIGH LIGHTS AND SIDE LIGHTS

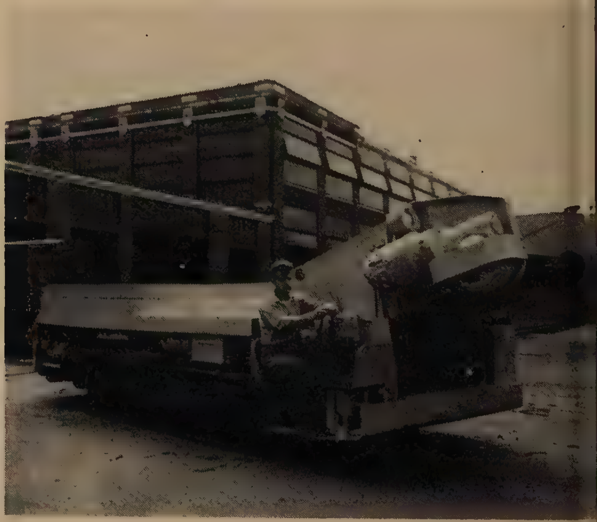
Shuttle Car for Mine Application

A new steel-track shuttle car of the cable-reel crawler type was recently announced for mine application. The new unit, designed for operation in close quarters, has a turning radius of from 14 to 16 ft.

Radically different from previous shuttle-car designs using rubber-tired wheels, the new unit provides for light ground-loading pressure per square inch by distributing weight over a large ground area.

Because no clearance is required for turning wheels, a much wider conveyor is built into the body of the track-laying car for the same over-all width. Improved maneuverability is illustrated by the shuttle car's ability to turn by locking one track completely.

Because of a wider conveyor, unloading speed is increased. Simplicity is stressed by the use of only two drive motors, one on each track, eliminating the complicated gears, drive shafts, and steering mechanisms required by the conventional four-wheel-drive, four-wheel-steer shuttle car.



Strange-looking electric vehicle designed for hauling coal in narrow veins far beneath the earth's surface

The new car is driven by two sealed-type 20-hp 250-volt series-wound motors driving each track through single-gear-reduction chain and sprocket. The gear case is an integral part of the motor. One sealed-type 3-hp compound-wound pump motor drives hydraulic auxiliaries. The conveyor chain is driven by two 5-hp 1750-rpm compound-wound gear-motors, with a 44:1 gear ratio.

The cable reel is hydraulically driven with sealed-type enclosure. A spooling device controls level winding. The reel is equipped with 600 ft of No. 3 two-conductor cable with ground wire, and guides permit reeling in either directi The hydraulic motor torque is automa cally compensated for reeling and unreeli cable pull.

All internal control elements, includi accelerating and headlight resistors, are sealed-type cases. Motor acceleration a reversing are accomplished by means magnetic-type contactors actuat through time-delay relays by a foot butt providing 3-step starting. Brakes on b traction motors provide for steering.

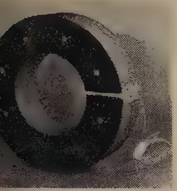
MPEDANCE NETWORK FOR TESTING LARGE INDUCTION APPARATUS

method for accurately measuring low-power-factor impedance ss of power transformers, induction regulators, and reactors

By S. C. LEONARD

Transformer and Allied Products Laboratory
General Electric Company

Stephen C. Leonard



THE production of larger power transformers and iron-cored reactors to meet the ever-increasing emand for more electrical power throughout the untry has created a number of measurement probms. One of the major problems is the accurate deterination of impedance losses.

The impedance power factor of large power transrmers, voltage regulators, and current-limiting rectors is inherently low, ranging from a few tenths of percent to five percent. For use under such conditions, nventional instrument transformers and associated rtable instruments have definite limitations. The loss dication on typical deflection-type wattmeters is adequate below five percent power factor without sorting to overloading the potential and current coils hich can introduce heating and indeterminate errors. t these extremely low power factors the correction r the phase angle of an instrument transformer injects significant error band since instrument transformers e normally certified to ±3 minutes in phase angle.

The more sensitive suspension-type instruments with ght-beam scales are excellent for certain types of evelopmental testing, but these are not as practical the sturdier pivot-type instruments for production sting and like the latter require both current and tential transformers to cover an extended range of rrent and voltage.

idge Networks

While bridge networks have been successfully apied at power frequencies for the commercial testing low-power-factor high-voltage capacitors for a numr of years,(1) the use of null balancing networks for e testing of induction-type apparatus was not atmpted until about twelve years ago. At that time the TH Laboratories in England(2) developed a toriod idge circuit to replace indicating instruments for the easurement of the impedance loss in their currentniting reactors. Shortly afterwards, the General lectric Company developed two a-c potentiometerpe networks using for reference standards air-core utual-inductance toroids similar to the BTH mutualductor design.(2) The first network(3) was designed ecifically for the commercial testing of air-core rrent-limiting reactors and consequently was limited to the measurement of linear impedances having lagging power factors below ten percent. The second network was designed for the developmental testing of either single- or three-phase iron-cored apparatus and has a phase-angle adjustment covering 360 degrees.

Experimental Measurements

Early experience with the experimental impedance network showed that null balancing type networks could be successfully applied to the impedance measurements of large power apparatus. Measurements at power factors below 10 percent were repeatable and eliminated phase-angle corrections for current transformers and instruments. Small differences in losses could be measured that were not detectable previously. The main drawback to the use of the impedance network was the necessity of maintaining the voltage and frequency constant during the time required to balance the network. When the power source and loading remained constant, measurement to a tenth of a percent was easily attained. At other times, a critical balance would be entirely obscured by relatively small changes in voltage or frequency. After an extensive investigation of the application of this type of network to the commercial testing of induction apparatus, it was found that both the voltage and frequency of the power source must be held stable to a few hundreths of a percent during balance. In addition, the null detector must have high discrimination between the fundamental frequency of balance and the harmonics generated by nonlinear loads. A frequency discrimination of at least 100 db to the third and higher harmonics is desirable.

Stabilization of Testing Power

Since the war, a means of stabilizing testing power(4) has been developed to a degree that has made the application of impedance networks practicable. This development, coupled with advances in the design of electronic detectors, has resulted in the accurate measurement of low-power-factor impedances of large induction apparatus on a production-test basis.

Basic Measuring Circuit

General Operation

The basic measuring circuit is shown in FIG. 1; the vector relationships are shown in FIG. 2. The heart

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1)Numbered references are listed at the end of the article.

of the measuring circuit is a simple a-c potentiometer with two quadrature arms (*A* and *B*) and a precision mutual-inductance reference toroid *M*. The voltage drops across the potentiometer arms are both proportional to the excitation voltage E_L, the drop across the *A* arm being in phase with E_L, while that across the *B* arm is in quadrature with E_L. A measurement is made by balancing the vector sum of the quadrature voltages E_A and E_B against E_M. The reference toroid voltage E_M is proportional to the load current I_L and in quadrature with it. Balance of the potentiometer dials R_A and R_B is indicated by a null response of the detector (*DET*). This null response also indicates zero load on the toroid secondary, which is a condition necessary for an accurate measurement. The values of impedance and watts loss of the apparatus under test are then readily calculated from the potentiometer dial readings, the toroid constant, and the nominal value of voltage or current.

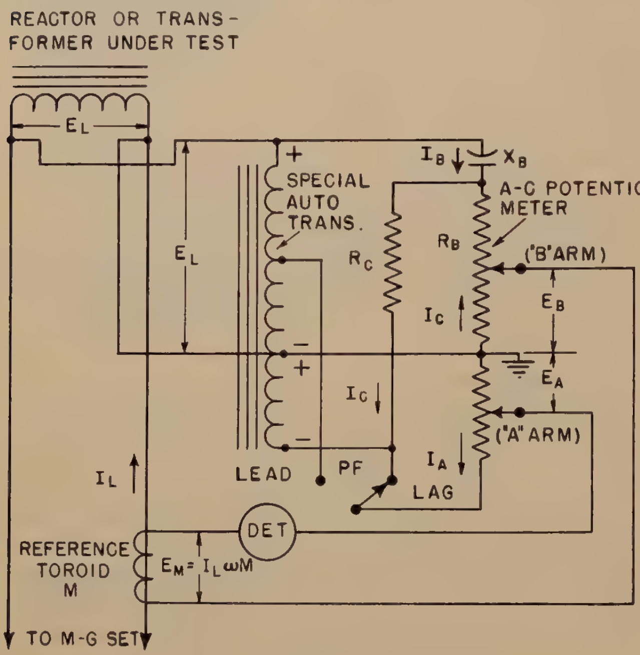

Fig. 1. Basic measurement circuit

Dial Arms

The in-phase dial arm R_A is a standard decade-type resistance potentiometer. The autotransformer provides a means of reversing the flow of current in this arm to provide the proper phase relationship for measurement at either leading or lagging currents.

The quadrature dial arm R_B is also a standard decade-type resistance potentiometer but is connected to the potential circuit through a series capacitor to provide a quadrature voltage drop across R_B. The ratio of X_B to R_B is made large to closely approximate a 90-degree relationship regardless of small variations in the test frequency. An exact quadrature relationship is obtained by bucking out the small amount of unwanted in-phase current flowing in R_B with an equivalent opposing current I_C. The amount of I_C fed into R_B is adjusted by means of the compensating resistance R_C.

The actual measuring network is shown in FIGS. and 4. The potentiometer dial arms are mechanical ganged to provide potentiometer-type operation. combination of tapped shunt and series resistances a used to extend the range of each of these arms.

Vector Analysis of Operation

The vector voltage relationship for balance with lagging-power-factor load is shown in FIG. 2(a). Sinc no current is drawn from the toroid secondary balance, E_M will lead I_L by exactly 90 degrees. Simila ly, if the apparatus under test were a pure inductanc E_L would also lead I_L by exactly 90 degrees. A stud

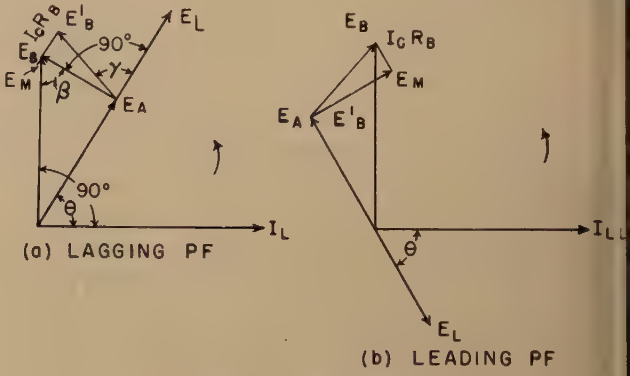

Fig. 2. Vector diagrams

of the instantaneous polarities and current directio in the basic measuring circuit (FIG. 1) will show tha E_A is always in phase with E_L during lagging-powe factor measurements. For the measurement of pu inductance, a single resistance potentiometer wou suffice since only the *A* arm would be required t obtain a balance; R_A is adjusted to be equal in magn tude to E_M. This illustrates why the network shown inherently accurate at small power factors and wh the *A*-arm dial reading is directly proportional to th reactive component of I_L or inversely proportional t the reactance being measured. In the practical cas E_L will always lead I_L by some angle θ that is le than 90 degrees. If the series capacitor in the *B* ar (FIG. 1) were a pure capacitance and the ratio of X to R_B infinite, then E_B would lead E_A or E_L by exact 90 degrees. Under this condition, the *B*-dial arm rea ing would always be inversely proportional to the re component of the impedance under test and the voltag drops E_A and E_B could always be adjusted to vectoriall balance with E_M regardless of the magnitude of th power-factor angle θ. Since the series capacitor in th *B* arm is not a pure capacitor, and since an infinit ratio of X_B to R_B is not practical, the *B*-arm voltag drop E_B will lead E_A by some angle γ that is slightl less than 90 degrees and thus cause a slight error i the quadrature relationship between the two arms. A exact quadrature relationship is obtained by using precision-type low-power-factor capacitor as a serie element, maintaining a high ratio of X_B to R_B (50 to or greater) and introducing a small voltage drop I_C R

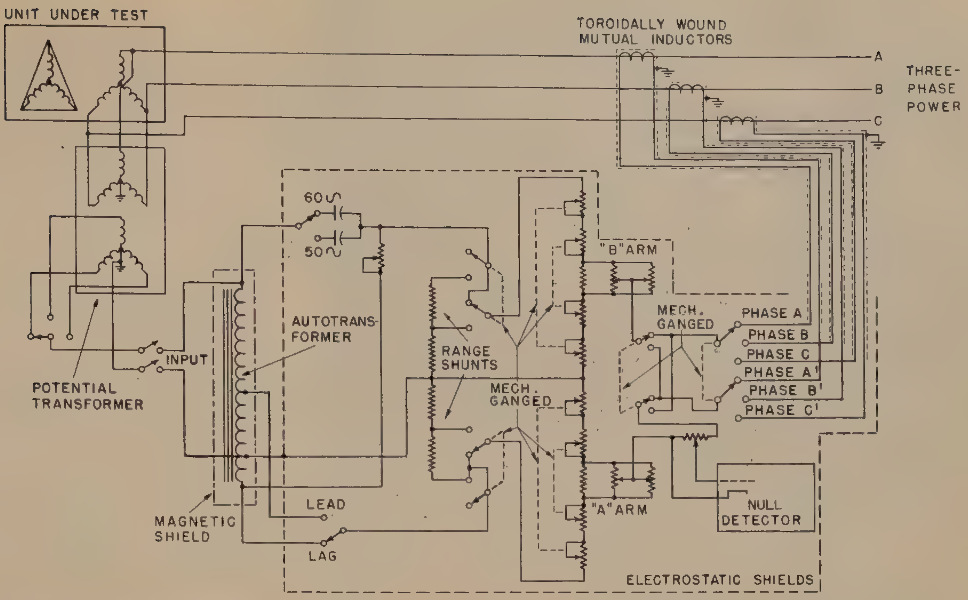

Fig. 3
Diagram of connections for measuring network

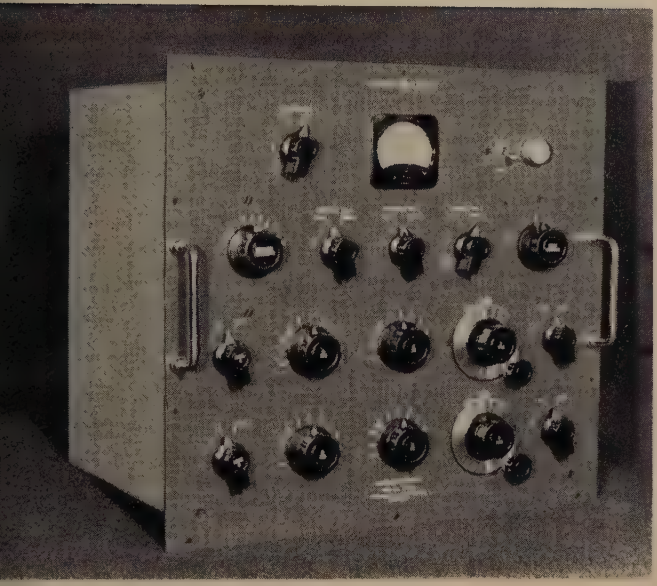

Fig. 4. Network panel assembly

ı the B arm that is in phase opposition with E_A. The se of a precision low-power-factor capacitor and of a igh ratio of X_B to R_B alone insures negligible error for ow-power-factor measurements and makes the B arm ndependent of small changes in frequency. The addiion of the compensation $I_C R_B$ insures negligible error ver the whole range of power-factor measurement. For larity, the error angle shown without compensation is reatly exaggerated in FIG. 2(a). In normal practice his angle is in the order of 1 degree.

FIG. 2(b) illustrates the vectorial balance of voltages or the measurement at leading power factors. Measureent in any other quadrant can be obtained by reversg the secondary toroid leads or the vector relation f E_M.

eference Toroids

The reference toroids are toroidally wound mutual ductors encased in thin split-copper shields. The econdary turns must be evenly spaced around the periphery and wound in such a manner that the plane of each turn is effectively parallel to the axis of the toroid. To avoid a complete turn in the plane of the secondary perpendicular to the axis of the toroid, the winding is either space-wound in one direction and then wound back interspaced in the opposite direction or close-wound in one direction with inter-turn crossovers and a single compensating turn brought back adjacent to the crossovers. The first method of winding used in the coil is shown in FIG. 5(a) and is the method advocated by BTH.⁽¹⁾⁽³⁾ The second method of winding is somewhat less complicated and appears to be equally effective. The second method is shown in FIG. 5(b).

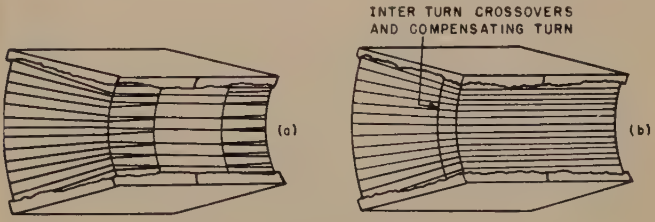

Fig. 5. Toroidal winding construction
(*a*). BTH type (*b*). GE type

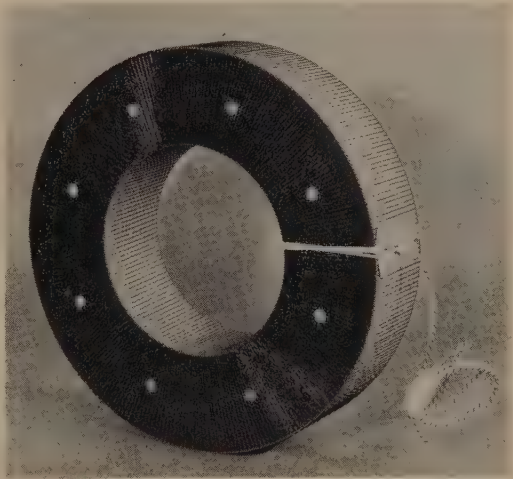

Fig. 6. Toroidal winding. This is of the BTH design shown in Fig. 5(*a*)

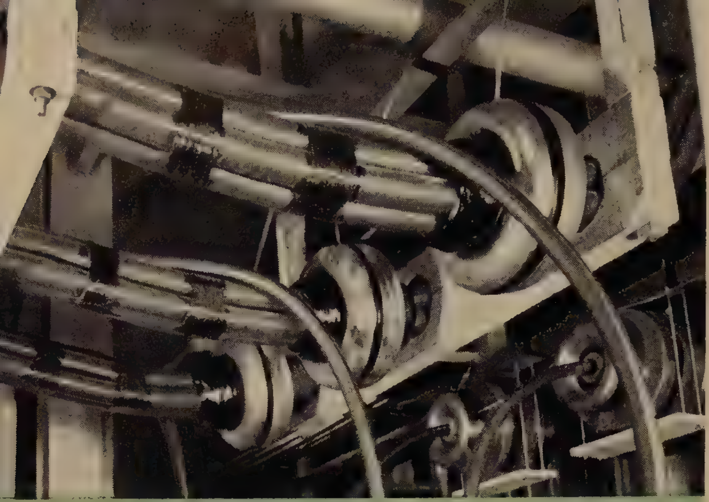

Fig. 7. Toroid installation

The actual toroids used in the application being described are precision-wound on molded-resin forms and cased in spun-copper shields to allow insulation of the primary conductors for operation at 30 kv above ground (FIGS. 6 and 7). The physical parameters are given in the following tabulation:

Toroid (Amp Rating)	OD	ID	Axial Length	Primary Turns	Secondary Turns	Impedance Constant K
1 to 10	12 in.	3.75 in.	5.00 in.	10	566	330
10 to 100	12 in.	3.75 in.	5.00 in.	1	566	33
100 to 3000	12 in.	6.25 in.	2.75 in.	1	276	5

The impedance constant K is an over-all constant that takes into account both the mutual inductance of the toroid and the voltage ratios of the A and B dial arms. The constant can be calculated from the physical dimensions of the winding, but in practice it is normally determined by a measurement of the induced voltage with a precision-type a-c potentiometer. The primary excitation current is determined by a simultaneous measurement of the voltage drop across a precision resistive shunt.

Calculations

Toroid Constant

For preliminary design purposes, the mutual inductance of the reference toroid is calculated from the physical dimensions of the winding form:

$$M = 0.0117\, N_p N_s h \log_{10} \frac{r_2}{r_1} \qquad (1)$$

where M = mutual inductance in microhenrys
N_p = number of primary turns
N_s = number of secondary turns
r_2 = outer radius in inches
r_1 = inner radius in inches
h = axial thickness in inches

The formula is based upon formulas derived by the Bureau of Standards⁽⁵⁾ for toroidal-type windings and has been found to be correct to about 5 percent without corrections for wire dimensions.

The true mutual inductance is determined from measurements with a precision a-c potentiometer.

$$M = E_M (10)^6 / I_L \omega \qquad ($$

where M = mutual induction in microhenries
E_M = volts induced in secondary
I_L = primary current in amperes
$\omega = 2\pi f$ where f is frequency in cycles

The impedance constant K is dependent upon th voltage ratio chosen for the potentiometer arms A an B (FIG. 1) and the mutual inductance of the toroid.

Let V_R = the voltage ratio of the potentiometer arm per unit of dial reading or the ratio of E_L to the volta drop per unit of resistance of R_A or R_B (FIG. 1).

$$\text{Then } K = V_R \omega M \qquad ($$

Impedance and Watts Loss

Let A and B = the dial arm readings
From FIG. 2(a) at balance

$$E_M = \sqrt{E_A^2 + E_B^2} = I_L \omega M \qquad ($$

$$\text{but} \quad E_A = A\, E_L / V_R \text{ and } E_B = B\, E_L / V_R \qquad ($$

$$\text{by substitution } E_M = \frac{E_L}{V_R} \sqrt{A^2 + B^2} = I_L \omega M \qquad ($$

$$\text{but} \quad Z = E_L / I_L \qquad ($$

$$\therefore \quad Z = V_R \omega M / \sqrt{A^2 + B^2} = K / \sqrt{A^2 + B^2} \quad ($$

$$\text{Watts} = E_L I_L \cos\theta \qquad ($$

$$\text{from FIG. 2(a), } \cos\theta = \cos\beta = E_B / E_M \qquad (1$$

$$\therefore \text{from (3) and (5), } \cos\theta = E_B / I_L \omega M = B E_L / K I_L \qquad (11$$

$$\text{or from FIG. 2(a) and (5), } \cos\theta = E_B / \sqrt{E_A^2 + E_B^2} = B / \sqrt{A^2 + B^2} \qquad (1$$

$$\therefore \text{from (9) and (11), Watts} = E_L I_L B E_L / K I_L = E_L^2 B / K \quad (1$$

$$\text{but from (8) } E = I_L Z = I_L K / \sqrt{A^2 + B^2} \qquad (14$$

$\therefore$ from (9), (12), and (14)

$$\text{Watts} = (I_L K / \sqrt{A^2 + B^2}) I_L (B / \sqrt{A^2 + B^2}) = I_L^2 K B / (A^2 + B^2) \qquad (1$$

Although the network shown in FIG. 1 does not provide readings directly in impedance ohms or watt los an average operator versed in routine transforme testing can easily determine these quantities from th dial readings by simple arithmetic.

$$Z = K / \sqrt{A^2 + B^2} \qquad (8$$

$$\text{Watts} = E_L^2\, B / K \qquad (1$$

$$\text{Watts} = I_L^2\, K B / (A^2 + B^2) \qquad (1$$

While normal excitation of the apparatus bein tested is held by means of a portable voltmeter c ammeter, the nominal value of voltage or current i used in the calculations. Thus the measured loss c impedance is independent of small variations in mete readings or inherent meter errors.

A potential transformer is normally used to isolat the potential circuit of the measuring network fro the apparatus under test and to extend its voltag range. When a potential transformer is used, the valu of K in the equations is multiplied by the ratio of th transformer.

Tare Corrections

For convenience, all power controls, instruments, and measuring circuits are permanently housed in a test berth which is usually located adjacent to the test area or pit. The over-all residual loss of the measuring circuits and instrumentation is normally referred to as the berth tare, which is determined either by actual measurement or by calculation.

The tare is taken by disconnecting the apparatus under test and measuring the residual losses of the potential transformer, instruments, and network with the test berth operating at the normal excitation voltage applied during test.

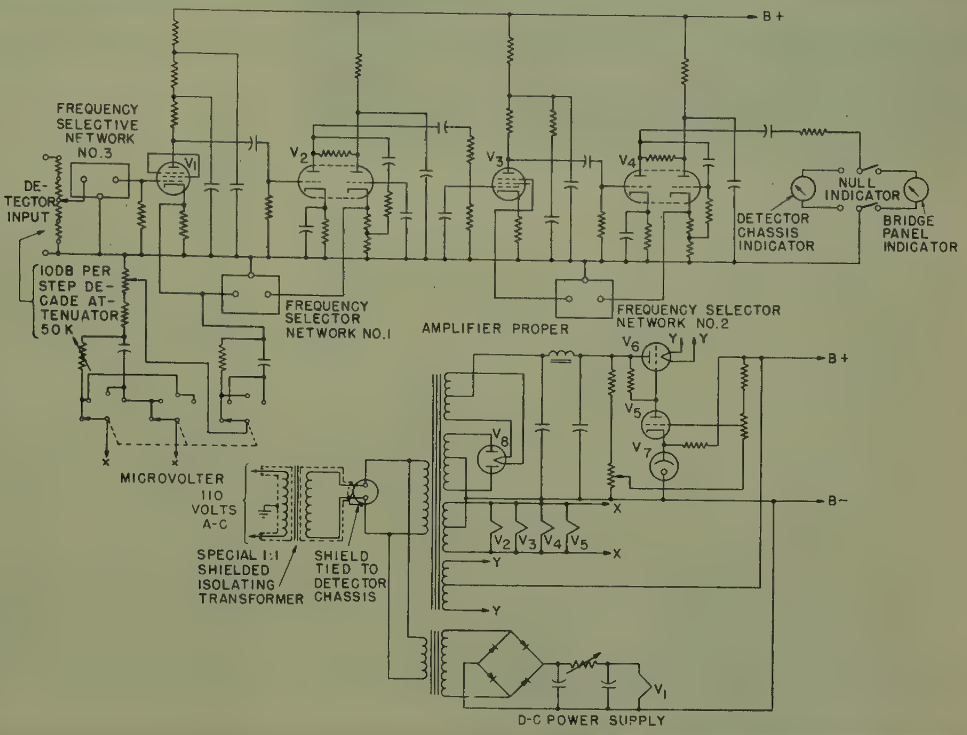
B+
FREQUENCY SELECTIVE NETWORK NO.3
V1
V2
V3
V4
DE-TECTOR INPUT
NULL INDICATOR
DETECTOR CHASSIS INDICATOR
BRIDGE PANEL INDICATOR
10DB PER STEP DE-CADE AT-TENUATOR 50K
FREQUENCY SELECTOR NETWORK NO.1
AMPLIFIER PROPER
FREQUENCY SELECTOR NETWORK NO.2
V6
Y
Y
B+
V5
V8
V7
MICROVOLTER
110 VOLTS A-C
X
X
B−
X
V2
V3
V4
V5
X
Y
SPECIAL 1:1 SHIELDED ISOLATING TRANSFORMER
SHIELD TIED TO DETECTOR CHASSIS
Y
V1
D-C POWER SUPPLY

Fig. 8. **Connection diagram of null detector**

For most commercial testing, the individual tares for the instruments, the potential transformer, and the network are calculated from known constants. This aves the time required to disconnect heavy leads and o make the extra tare measurement. The berth tare is generally small compared to the losses present in large apparatus, so that errors in the determination of the tare loss are normally a second order effect and can be neglected.

Measurements at extremely low power factors such as those encountered in iron-cored current-limiting eactors are more critical. For such measurements, the berth tare is generally measured and correction made or the phase angle of the potential transformer.

Null Detector

The detector is completely a-c operated, being a high-ain vacuum-tube amplifier feeding a small panel-type opper-oxide microammeter as the null indicator (Figs. and 8). To allow the measurement of nonlinear imped-nces, two frequency-selective feedback circuits are mployed in cascade to provide an attenuation to harmonics of 100 db or more. The attenuation networks themselves are of the RC-parallel-T type introduced by H. H. Scott.(6) The amplifier and its associated power supply are isolated from the 115-volt a-c shop line by means of a special shielded transformer.

The over-all gain and selectivity of the amplifier is such that a fundamental voltage unbalance in the measuring network of one or two microvolts can be detected in the presence of harmonic voltages in the order of 0.25 volts.

Measurement Range

Current	1 to 3000 amp	
Voltage	40 to 150 volts	(network alone)
	Up to 30 kv	(with potential transformer)
Power factor	0 to 1	(0 to 360° angle)

Accuracy

Network arms		±0.2 percent
Toroid	(Impedance constant)	±0.2 percent
	(Phase-angle error) less than	0.25 minute
Potential Transformer	(Ratio)	±0.1 percent
	(Phase angle)	±1 minute

Over-all

at 5 percent power factor	±1.2 percent
at 1 percent power factor	±4.0 percent
at 0.5 percent power factor	±8.0 percent

It will be noted from the tabulation that the over-all accuracy at low power factors is limited mainly by the accuracy to which the phase angle of the potential transformer can be determined. The Bureau of Standards will only certify instrument transformers to ±3 minutes. With experienced personnel, the absolute phase angle of a potential transformer can be deter-

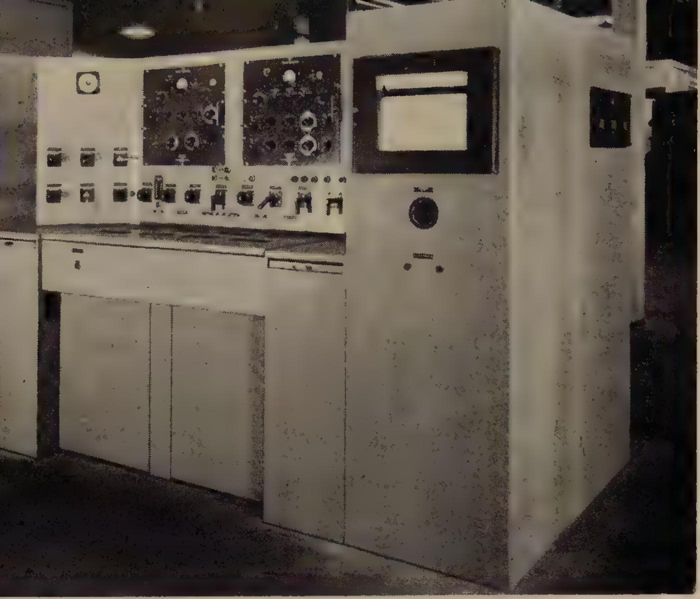

Fig. 9. Modern power transformer test berth

mined to ±1 minute using modern calibrating equipment. Although modern bridge networks provide calibration readings to 0.1 minute, it is considered prudent to allow a 1 minute tolerance for inherent instability of the device being calibrated and the associated measuring circuit.

Tests at 2 percent power factor without a potential transformer in the circuit show that the described impedance network has a probable error of ±0.3 percent compared with errors ranging from 3 to 8 percent for a carefully calibrated low-power-factor portable wattmeter.

Applications

The impedance network described has been installed as an integral part of the modern power transformer test berths such as that shown in Fig. 9. It can be used for all impedance-loss testing with the possible exception of core-loss tests on power transformers where harmonics in both the voltage and current waves could cause appreciable error. It is particularly adapted to the measurement of the impedance losses in current-limiting reactors and voltage regulators, and for measuring the short-circuit impedance of large power transformers at power factors below 10 percent. It will be extremely helpful in determining the point at which short-circuited heat runs become stable, thus saving many hours of running time and in many instances the need for reruns.

The network is used for the measurement of both single- and three-phase apparatus. The circuit connections for single-phase measurements are indicated in Fig. 1. Three-phase measurements are made on a phase-to-phase basis, duplicate toroids being installed in each of the three-phase supply lines. This is the same procedure that is followed in the three-wattmeter method of measuring losses using a single wattmeter to take the required three readings.(7)

At the present time an extensive investigation is being made to determine the possibility of applying this network in the field of core-loss testing.

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(5)"Radio Instruments and Measurements," Bureau of Standards Circular No. 74.

(6)"A New Type of Selective Circuit and Some Applications," by H. H. Scott, *Proceedings, Institute of Radio Engineers*, vol. 26, February 1938, p. 226.

(7)"Three-wattmeter Method of Measuring Loss," Ralph R. Lawrence; *Principles of Alternating Currents*, McGraw-Hill Book Company, Inc., New York 1935, p. 356.

HIGH LIGHTS AND SIDE LIGHTS

Aerial Traffic Lights

Busy street corners aren't the only places to find traffic signals. They're also lighting up in the skies these days, as Boeing KB-29 and KC-97 tanker airplanes refuel bombers in midair. And they are used for both day and night in-flight refueling operations by the U.S. Air Force.

When the Boeing Flying Boom, through which the fuel is pumped to the receiver airplane, was first developed, directions from the boom operator to the receiver pilot were issued by radio only. But more recently the "traffic lights" have been installed on the bottom of the tankers to aid in keeping the two planes in proper position while fuel is transferred.

The lights, four red and one green, are automatically triggered by microswitches connected with the boom. Lettering on the red-lighted oblong panels reads UP, DWN, FWD, and AFT, to advise the receiver pilot when his plane is out of position. Use of the new sealed-beam lamp developed for this application was recently described as one of the significant lighting advances of the year.

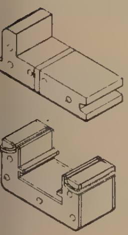
Green center panel remains lighted when the two airplanes are in proper refueling contact

When the telescoping section of the boom is extended to the proper length and the boom's elevation angle is correct, the green light glows; but should the airplane receiving fuel move outside of this position, the green panel darkens and either one or two of the red lights flash on to tell the receiver pilot where to move.

Instruction in the night refueling operations was started recently at Castle Air Force Base in California, with the 93rd Air Refueling Squadron becoming the first Air Force group to receive such training. Some of the crews were reported to be a bit nervous on their first after-dark hook-up, but the "blackness fear" soon was lost and night transfers are now being made as smoothly as those in the daytime.

MODERN LOW-VOLTAGE A-C MOTOR STARTERS

Design details to be considered in the development of a new line of starters, for increased life and reliability through better utilization of material



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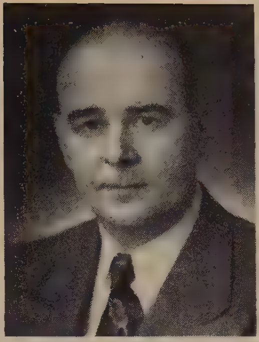

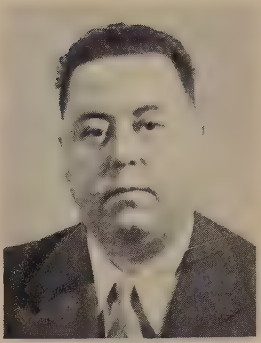

G W Heumann   B J Mimken

THE phenomenal growth of American production per man-hour, which has far outstripped the rest of the world, is due to the large amount of motor horsepower backing up each workman. According to the latest motor census, taken in 1947, each production worker in industry is backed up by 7.2 horsepower in electric motors.

Largest in quantity of all motors built is the squirrel-cage induction motor which, in sizes up to approximately 15 hp, can be found everywhere on production machinery. Every motor needs a starter. Magnetic starters, which offer the advantage that they can be mounted remote from the operator's control station, are the largest-selling starters in the integral-horsepower sizes, and they represent one of the most important lines of industrial controllers.

Lift-type Contactors

A complete starter for squirrel-cage motors consists of a contactor and overload relays. Lift-type contactors, such as that shown in Fig. 1, were introduced to the trade some 15 years ago, and they are used today. Up to NEMA Size 3 (100 amp) this design is used by practically all motor-controller manufacturers. The principal advantage of this design is its mechanical simplicity: the magnet produces a straight-line motion that is transmitted directly to the movable contacts; there are no pivots and bearings; thus, mechanical wearing surfaces are reduced to a minimum. By proper design of the mechanical and electrical parts, much longer life can be obtained than had been possible with former designs of a-c contactors, with rotating shafts and bearings.

A considerable amount of developmental work is necessary to work out details of design. Theory may guide the contactor designer and establish fundamental principles. However, it is not convenient to calculate every detail of so complex a mechanism as a contactor. A well-equipped laboratory must be available to the designer so that data can be obtained for checking every step in the development of a new contactor design.

Arc Interruption

The most important and fastest-wearing parts are the contacts which have to carry and to interrupt the motor load current. NEMA standards stipulate that, when rated motor currents are carried, temperature rise of contacts shall not exceed 65C. They also stipulate that, to allow for interruption of locked-rotor current of the motor (which is the highest operating overload a contactor can be called upon to handle) the contactor must be capable of interrupting ten times its rated motor current. A certain amount of burning on account of arc interruption is unavoidable. By proper contact design and by choice of proper contact material, burning of the contacts can be reduced to a reasonable amount.

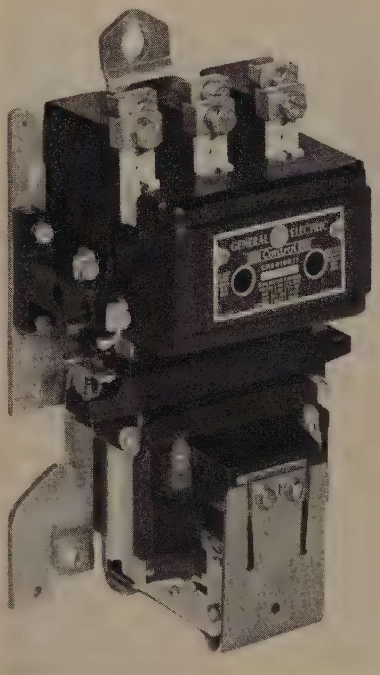

Fig. 1. Lift-type contactor, NEMA Size 2 (50 amp)

An exploded view of the contact structure of a Size 3 contactor is shown in Fig. 2. Contacts here are double-break silver contacts, a movable bridge making contact with the stationary contacts of each pole. There are no blowout coils. The contacts are enclosed in a cavity within the arc chute, which serves to confine the arc and to separate the poles from each other. Arc extinction takes place as a result of cooling on the surfaces of the arc-chute cavity. On contactors Size 2 and larger, metal inserts are molded in the arc chute to assist in cooling the arc. A certain amount of magnetic blowout effect is obtained by the configuration of the contacts and the current-carrying parts. This blowout effect has the tendency to stretch the arc and to force it against the walls of the arc chute, thereby enhancing the cooling effect.

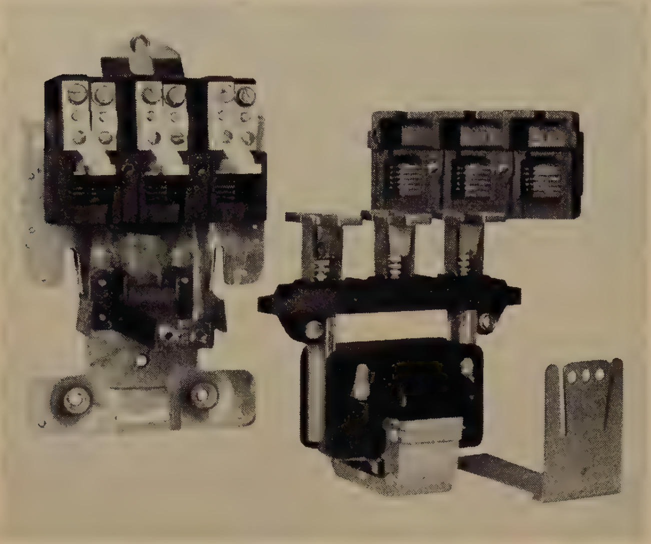

Fig. 2. Lift-type contactor, NEMA Size 3 (100 amp); exploded view, showing details of contact construction

Configuration of the arc chute and size of the cavity are important. If the cavity is too small, it becomes excessively ionized and the arc is not extinguished. If the cavity is too large, the arc is not cooled effectively. Best arc-chute design is determined experimentally by load tests. The contactor is loaded with a motor of the largest size within its anticipated rating, and the motor rotor is blocked mechanically to simulate a locked-rotor condition. Load tests on various developmental arc-chute designs are conducted until failure occurs; the most efficient arc-chute design is thus determined.

Speed of contact opening is also of importance. For the interruption of d-c arcs, it is essential that the contacts be parted at high speed in order to elongate the arc rapidly. For interruption of a-c arcs, on the other hand, high contact-opening speed is not desirable. Best interruption is obtained when the arc is extinguished naturally as current passes through zero and does not restrike during the subsequent half-cycle. A moderate initial contact-opening speed is preferred. Contact opening should not be too slow; otherwise, the arc burns for too many cycles before it extinguishes.

Contact Material

Unfortunately, nature has not provided us with an ideal contact material. All known contact materials and alloys have their good points and their weak points, and not one single material combines all desirabl characteristics. The two contact materials of practica importance for contactors are copper and silver. Ex tensive tests of contact behavior under actual load currents have indicated that contact life is greatl affected by rate of oxidation of the contact surface Silver contacts, made from cold-drawn stock, have high degree of surface hardness. Consequently, thei rate of surface oxidation is comparatively low. Ex perience gained from actual installations and from laboratory tests has proved that for general-purpose contactors of moderate size silver contacts are superio to other contact materials in point of contact life

Magnet Structure

The laminations of which the magnet consists are stacked and riveted under pressure. The whole stack is then annealed to relieve stresses and to improve its magnetic qualities. The moving armature, which carries the contact support, is comparatively heavy. Thus, a high opening force is imparted upon the contacts when the magnet is de-energized—a feature that is beneficial to contact-opening performance during rapid jogging. The armature is not rigidly connected to its guide, but is supported on a spherical seat. Therefore, the armature is self-aligning when the magnet closes, and good seating between the movable and stationary parts is insured, resulting in quiet magnet operation.

When the coil is de-energized, it is essential that the magnet drop out cleanly, without any tendency to stick on account of residual magnetism. Because of hysteresis, the flux in any iron-core magnet does not drop to zero when the magnetizing current is interrupted. Since, with no air gap in the magnetic circuit, the pull due to residual flux may be sufficient to prevent the armature from dropping out, it is accepted practice in electromagnet design to introduce an artificial air gap in the magnetic path. As a result, the residual flux at zero magnetizing current becomes smaller, and the corresponding pull is reduced below the threshold value at which the armature begins to drop out. Of course, the

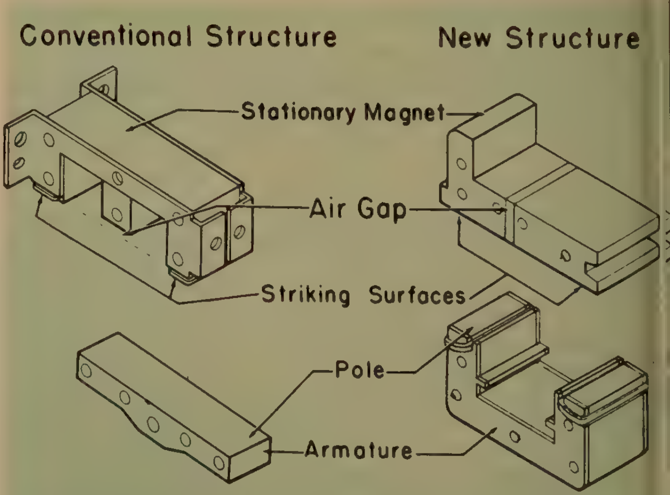

Fig. 3. Conventional and new designs of air gap in a-c magnet

ir gap is kept as short as possible, so that the magnetizng current is not increased excessively.

Conventional magnets, as shown in Fig. 3, have a hysical air gap in one of the striking surfaces. Such n air gap works very well as long as the magnet is ew. However, on any a-c magnet the laminations, in me, become flattened and mushroomed at the suraces on which the armature strikes the stationary nagnet. When a contactor is called upon to operate requently, the physical air gap will eventually be reuced, and it may eventually disappear altogether. o overcome this disadvantage, a permanent air gap n the form of a wafer of nonmagnetic material has een introduced in the stationary part of the magnet. he side-plates of the magnet are of stainless steel, so hat the nonmagnetic wafer is not shunted out. Since he permanent air gap is located away from the strikng surfaces of the magnet, it is unaffected by any preading or mushrooming of laminations, and its fficacy does not change with age. Life tests have roved that magnet life is increased by the permanent ir gap, since it eliminates magnet failure due to disppearance of the physical air gap.

Two pole shaders are provided, one in each leg of he armature, to obtain a quiet magnet at coil voltages elow rated voltage. To be effective, a pole shader has o have a certain resistance. Hence, brasses and bronzes ave been used to a large extent as pole-shader maerials. Since they are located close to striking surfaces, ole shaders are subject to high impact stresses, and ole-shader breakages are a problem to be considered n magnet design. Tests with various pole-shader naterials have brought out that certain aluminum lloys have suitable specific resistance and desirable nechanical properties. Using aluminum alloy reduces ne mass of the pole shader, thereby reducing the endency of breaking under the shock of magnet closng.

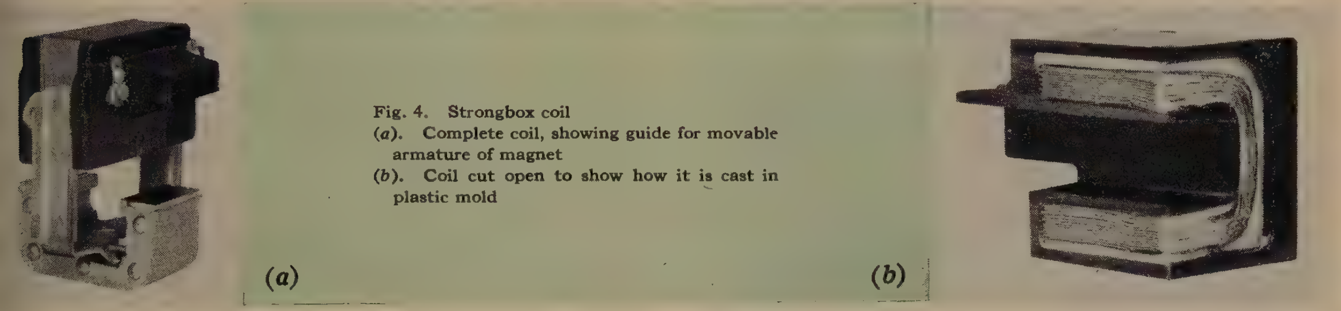
Fig. 4. Strongbox coil
(*a*). Complete coil, showing guide for movable armature of magnet
(*b*). Coil cut open to show how it is cast in plastic mold

trongbox Coil

The magnet coil is encased in a molded box of the ype shown in Fig. 4(*a*). The side of the box forms the hannel guide for the armature, which in turn supports ne movable-contact structure.

Coils are wound of fine copper wire that is insulated y a coating of enamel. Modern enameled wires such s Formex* possess great improvements in insulating qualities and in the uniformity with which the coating is applied, resulting in a thinner coating with fewer bare spots. Better wire enamels have eliminated coil failures due to short-circuited turns as a major source of trouble. However, another important problem to be considered in coil design is failure due to open-circuiting. Such failures occur generally at the point where the terminal, or lead-in wire, is soldered to the coil wire, and they may be due to either one of two causes.

First, there may be mechanical vibration. Terminals, or lead-in wires, are held in place by a wrapping around the outside of the coil. Experience and test have indicated that solid control wire, connected to coil terminals, is apt to transmit vibrations to the coil terminals. Stranded control wiring has recently gained greater acceptance. A second reason for open-circuiting is corrosion of the soldered joints. Since coils are alternately heated and cooled, moisture could easily penetrate even a tightly wrapped coil that is left untreated. The conventional technique is to impregnate coils by insulating varnish under pressure and heat, to make them impervious to moisture.

An advance in coil manufacture has been the development of a technique of casting coils with permafil, formerly called solventless varnish. Ordinary varnishes contain some solid resin dissolved in a liquid solvent. During the coil-impregnating process the solvent evaporates and the varnish remains as a hard mass, in which minute checks and cracks may form, permitting the entrance of moisture. Permafils are liquid compounds with a remarkable ability to penetrate the finest cracks and crevices. As they solidify, hardening takes place without any evaporation.

A coil that has been wound is cast in a block of permafil, forming a rigid assembly shown in Fig. 4(*b*). The permafil holds terminals firmly in place, and it protects the coil windings against mechanical injury as well as against attack by moisture. Furthermore, the intimate bond between permafil and winding provides for a path of low heat resistance between the winding and the outside, which aids in the dissipation of heat from the coils.

Mechanical Interlocks

Reversing starters are used to start reversible motors in either direction; they contain two contactors—one for each direction of rotation. Careful consideration must be given to the problem of how to prevent both contactors from being closed simultaneously, thus short-circuiting the power supply. For this purpose proper interlocking must be provided.

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*Registered trade mark of General Electric Co.

In the smaller starter sizes utilizing lift-type contactors, moving masses are light, and pickup and dropout are fast. Magnet strokes are fairly short, and normally closed electrical interlocks are not easy to keep properly adjusted. The reversing starter illustrated in Fig. 5 is equipped with a so-called interference-type interlock, which consists of two rotating levers, one for each contactor. The levers are so shaped that neither contactor can pick up unless the magnet of the other contactor has dropped out completely. Exhaustive tests have proved that this type of mechanical interlocking provides reliable means for interlocking two contactors, whether new or worn, against each other, and no additional electrical interlocking is necessary.

Overload Protection

Protection against operating overload is provided by thermal overload relays, which have generally been accepted by the trade as the most suitable type of relay for protecting general-purpose motors. The preferred construction, at least for smaller-size starters, is the use of single-pole relays mounted right on the contactor frame, as can be seen in Fig. 5.

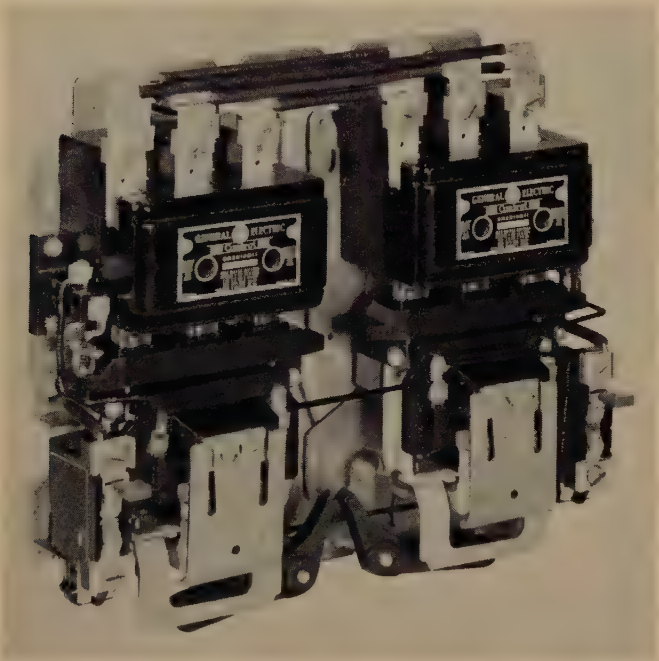

Fig. 5. Reversing starter, NEMA Size 2 (50 amp) with "interference" type mechanical interlock. Overload relays are shown at the right and left, beside the contactors' moving elements

In designing the tripping characteristic of the overload relay, it is necessary to consider tripping on slight overloads, permitting the motor to carry an overload just as long as it can without injurious overheating. When the motor is stalled, the relay must trip sufficiently fast to prevent possible serious damage to the motor windings, which are subjected to something like six times normal current without the cooling effect o windage.

Bimetallic and solderfilm relays have been develope to a high degree of perfection, and both types hav found widespread use in industry. There is one poin of difference between the two types of relays that i worth considering. Solderfilm relays, in general, ar available only for manual resetting, since an automati resetting device would be too complicated to be practical. Bimetallic relays, on the other hand, can be s built that by a simple adjustment, requiring no tools they can be either manually or automatically reset This is one of the reasons why a bimetallic design wa chosen for the starters forming the subject of thi article.

Combination Starters

Under the requirements of the National Electrica Code, every branch circuit feeding motors must b protected against the devastating effects of shor circuits. General-purpose a-c contactors—designed under NEMA standards, to interrupt ten times thei rated motor full-load current—are capable of interrupting operating overloads, but not the high current that may flow under fault conditions. The magnitud of overload currents depends on the motor size. Th magnitude of short-circuit currents depends, not o motor size, but on the characteristics of the powe system to which the controller is connected.

To provide full protection of the power system against short circuits, to protect the motor branch circuit conductors, and to protect the starter itsel against destruction, it is necessary to back up the contactor by devices that are capable of interrupting short circuit currents with safety and fast enough so tha the let-through energy does not exceed thermal limitations of the starter. Two kinds of devices are recognize by the National Electrical Code—namely, time-limit circuit breakers and fuses. These protective devices may be provided as separate units apart from the starters. However, there is a definite trend toward the use of so-called combination starters, which include a standard starter plus a circuit breaker or fused motor circuit switch in a common enclosure.

To the user, combination starters offer the following principal advantages: one unit, instead of two, has to be mounted and installed; and interconnecting wiring between protective device and starter need not be run through a conduit, but is included in the unit. All parts of the combination starter, including the wiring, are so designed and correlated that they can withstand the effects of available short-circuit currents for which the unit is rated.

Shown in Fig. 6(*a*) is a combination starter with a molded-case air circuit breaker for short-circuit protection. Such starters can be connected to power systems that have available short-circuit currents up to 15,000 amperes at the point of starter installation. The starter is mounted in a general-purpose enclosure so designed that the breaker can be operated nd the overload relays reset without opening the nclosure cover. Fig. 6(*b*) illustrates a combination tarter with fusible motor-circuit switch. Fuses may ither be ordinary NEC cartridge fuses or current-miting fuses, which are designed and tested for in-erruption of much higher levels of available short-ircuit current.

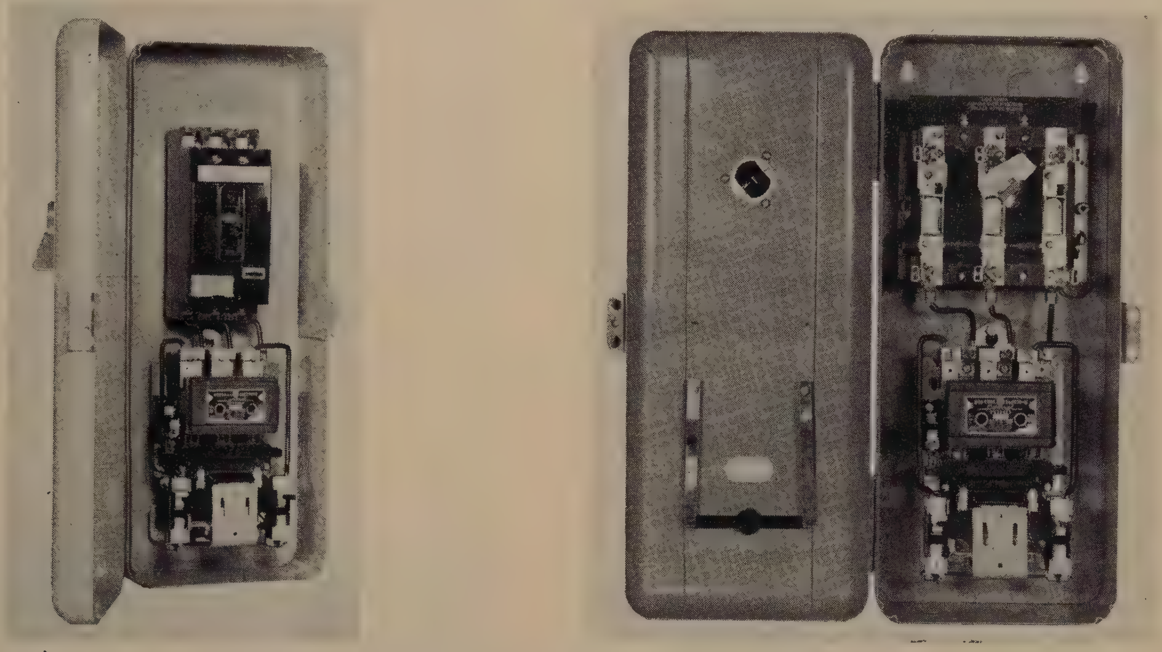
(*a*) (*b*)

Fig. 6. Combination starters, NEMA Size 3 (100 amp): (*a*). With molded-case circuit breaker; (*b*). With fusible motor-circuit switch

hermal Co-ordination

Ratings of fuses and circuit breakers used in com-ination starters must be sufficiently high to avoid terruption of the motor power circuit during starting. n the other hand, their rating should be as low as asible to obtain quick circuit interruption under ult condition and to keep the energy, flowing through e branch-circuit conductors and the starter during a ult, at the minimum. On the basis of many years of erating experience, the National Electrical Code has tablished tables for maximum settings or ratings of cuit breakers and fuses that range, according to otor types, between 150 and 300 percent of motor ll-load current.

Exceptions may be taken to these tables, should rticularly severe starting conditions make it im- ssible to start the motor without tripping the eaker or blowing the fuse. The Code, however, states at the circuit-breaker trip setting or the fuse-current ing should not exceed four times the full-load current the motor with which the starter is used. This use has been inserted to prevent possible melting of overload-relay heaters, which might set off a short cuit within the starter, with resultant severe mage.

The Code makes no choice between circuit breakers l fuses for short-circuit protection. The following nts, however, may be considered. Motor starters of Size 3 or smaller have relatively limited thermal capacity. Overload-relay heaters for smaller motor sizes are wire-wound, and current-carrying parts may melt quickly when exposed to the high initial short-circuit current. Fuses generally interrupt high short-circuit currents faster than do circuit breakers, hence fuses afford better protection for smaller-size starters.

Molded-case circuit breakers cannot be obtained with trip ratings of less than 15 amp. Hence, for smaller motors than 3 hp at 440 volts, having a full-load current of approximately 4.5 amp, the Code requirements given here cannot be met. This is an added reason why, for smaller sizes of combination starters, protection by fuses is preferred.

Circuit breakers are preferred by many users because the inconvenience of replacing blown fuses is avoided. Size 4 and larger starters have comparatively greater mass in their current-carrying parts and, consequently, greater heat-storing capacity, and overload-relay heaters are made of strip instead of wire. Therefore, most users prefer circuit breakers for Size 4 and larger starters.

JIC Construction

The Joint Industry Conference of Automotive Manufacturers has issued a "JIC Standard" governing the design of electrical equipment for use on machine tools and other production machines in the automotive industry. This standard has been developed in the interest of safety and continuity of service. A combination starter meeting the JIC requirements is illustrated in Fig. 7.

Disconnecting means, operable from the outside, are provided by a motor-circuit switch, which may be fused. A control-circuit transformer is included to reduce the contactor coil voltage to 110 volts, so that push buttons and other pilot devices are not subjected to line voltage. The enclosure, which meets NEMA Type XII requirements, is especially designed for mounting on production machines.

The box is of all-welded construction, and all seams are tight, so that no oil or coolant can enter through the back or the sides. There are no mounting holes, a separate supporting plate being welded to the back. The cover is hinged and gasketed, to provide a semidust-tight joint between cover and box, and is held closed by screws, requiring a screwdriver for opening. Provision is made for padlocking the cover.

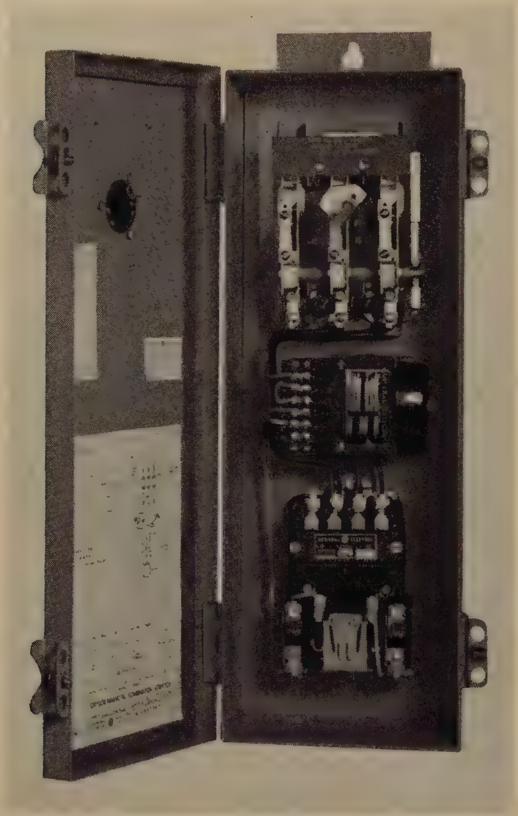

Fig. 7. Combination starter, NEMA Size 1 in NEMA Type XII enclosure, designed to meet JIC Standard

Control Centers

When a number of motors are installed in a plant within a comparatively limited area, the starters for such motors may be combined in a co-ordinated structure called a control center (Fig. 8). A control center, serving to control power-utilization apparatus, consists of vertical sections, each containing several compartments in which combination starters are installed. Each compartment contains the starter for control and protection of the motor, as well as the circuit breaker or fused switch for branch-circuit short-circuit protection.

Several vertical sections form a line-up, with a bus compartment at the top that contains the main power buses, to which the starters are connected through vertical risers. All bus work is properly spaced and braced to withstand the forces of the maximum available short-circuit current for which the equipment is d signed. The control center shown in Fig. 8 contai molded-case breakers; thus its interrupting capacit would be 15,000 amp. To the user, the control cent offers the advantages of reduction in installation tim and expense, and the assembly represents a c ordinated system, properly designed for its rated shor circuit interrupting ability.

Conclusion

The development of a new line of motor starters is major design-engineering undertaking. Knowledge applied physics, mechanical and electrical engineerin metallurgy, materials chemistry, and other fields science and engineering are utilized in working out th design details. Manufacturing methods must be scru tinized before the design can be frozen. While theor and analysis are necessary to evaluate design principle a well-equipped laboratory must be at the designer disposal so that those details which do not yield readil to analysis may be worked out experimentally. Th result of the design effort invested in the new line motor starters is increased life and reliability throug better utilization of material and better control of i properties.

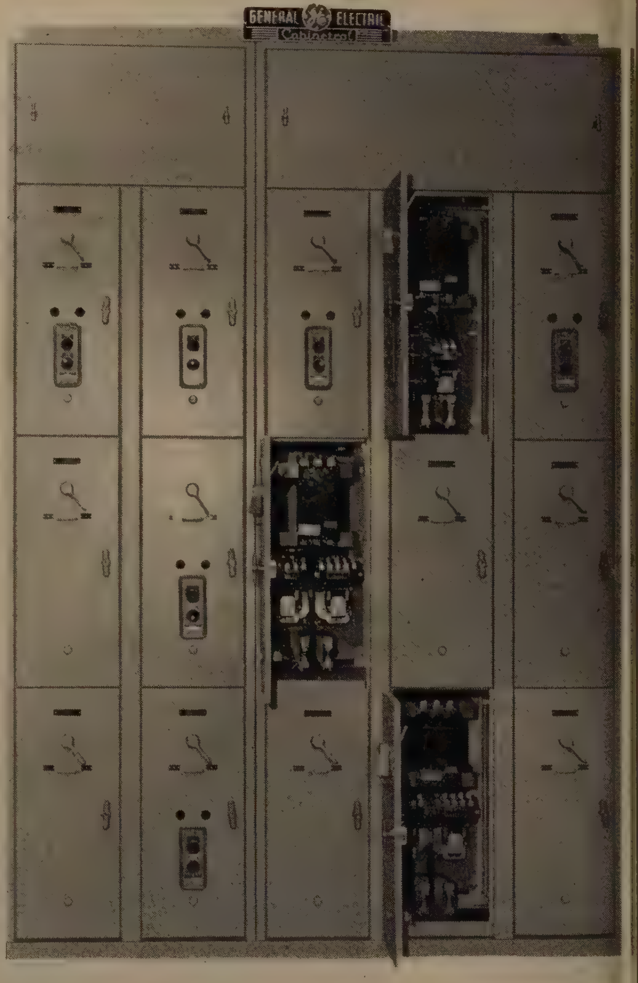

Fig. 8. "Control center" assembly of combination starters

ERVOMECHANISMS

ctors of stability and accuracy in automatic ntrol systems, and the development of means solving the related engineering problems

By HAROLD CHESTNUT and ROBERT W. MAYER

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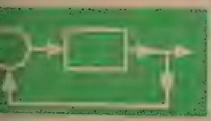
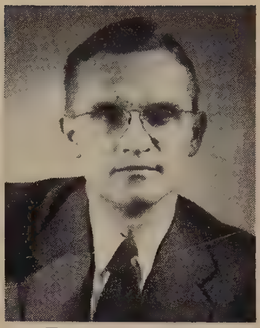


Harold Chestnut



R.W. Mayer

ECENT trends in the development of modern civilization have been in the direction of greater ıtrol. With the advent of the steam engine and the terial improvements brought about by the industrial volution, man has had available greater quantities power for his use. To utilize this power effectively, has been required to learn how to control and how to gulate it. The increased interdependence of individuals d groups of individuals upon one another during this riod has made it necessary for a greater measure of gulation to be exerted in the field of social activity well.

As part of the control process, whether it be of rsons or of things, certain standards are established. e performance of the equipment or of the individual compared to these standards, and according to the ference, appropriate action is taken to bring about a ser correspondence between the desired objectives d the actual performance. Examples of this type of gulating action are common in the operation of production or accounting groups in business as well as in operation of mechanical, electrical, thermal, and ner engineering equipment.⁽¹⁾ In some of these regued systems a long interval of time occurs before the formance being controlled is compared to the ded objectives. An annual manufacturing inventory a quarterly financial statement illustrates this point. r the automatically controlled engineering equipnt, the comparison may be made many times per ond. The point of interest is that the need for good ıtrol is present in many phases of our existence. e problem is to determine the desired objectives and best ways of producing these objectives. Although material of this article is limited to a study of probıs pertaining to the field of engineering applications ıutomatic control, there is the possibility that some the philosophy of feedback control set forth here ht be employed to advantage for other forms of trol problems.

ortunately for engineers, the desired objectives for ir equipment are fairly well defined and the means measuring the performance of this equipment are tively simple and accurate. For example, it is ded that the voltage and frequency of a power system be maintained within certain tolerances,⁽²⁾,⁽³⁾ that the speed or position of a motor shaft should obey certain prescribed conditions,⁽⁴⁾ or that the motion of one instrument or shaft should faithfully duplicate the motion of another.⁽⁵⁾,⁽⁶⁾ All these are problems in which the nature of the control requirements and references for describing these requirements can be established fairly well in advance. The meters, oscillographs, or error-sensing elements for determining the quality of performance are generally available.⁽⁷⁾,⁽⁸⁾

The advances of the technical arts have made available, in form suitable for control, amounts of power with high speeds of response such that man is unable to compete with machines for the power portion of the control. Furthermore, in the measuring or error-sensing portion of the control, instruments are in many cases more accurate, more rapid, more reliable, and cheaper than a human being who might be called upon to do a similar job manually. Thus man has found means for having some of his mental labor as well as much of his physical work done by machines. With these power and sensing means available, the field of automatic control is opened to relieve man of many of the monotonous and disagreeable aspects of many routine tasks and to make possible the accomplishment of labors that are humanly impossible. It is these features that make automatic control so attractive. Not only is it possible to reduce the amount of manual labor required, but it may also be possible to achieve a higher degree of performance than would otherwise be possible.

In this article the general form of the feedback control problem is presented. The factors of stability and accuracy associated with such a control are indicated. Next the means that have been developed for solving these engineering problems are described. To emphasize the various phases of the actual solution to the design problem, the general steps in solving a typical control problem are outlined. A brief review is presented of the development of the regulator and servomechanism arts up to the present time, when they are being merged to form the more unified science of feedback control systems. An attempt is made to indicate the direction that will be taken by future developments in the field of automatic control.

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is article constitutes the first chapter of the book *Servomechanisms and lating System Design*, Vol. I, by Harold Chestnut and Robert W. Mayer, shed by John Wiley and Sons, Inc., New York (1951). It is reprinted by permission of the authors and publisher.—EDITOR.

⁽¹⁾Numbered references are listed at the end of the article.

FEEDBACK CONTROL SYSTEM

The terms servomechanism and regulator have been described and defined many times in the literature. As used here, they refer to a feedback control system in which the difference between the *reference input* and some function of the *controlled variable* is used to supply an *actuating error* signal to the control elements and the controlled system.(9) The amplified actuating error signal endeavors to reduce to zero the difference between reference input and the controlled variable. A supplemental source of power is available in such systems to provide amplification at one or more points in the feedback control system, so that the possibility exists for self-excited oscillations or instability.

FIG. 1 is a block-diagram representation of a simplified feedback control system. In addition to the principal variables, described in the preceding paragraph and shown by the solid-line portions of the diagram, the *desired value*, the *indirectly controlled quantity*, and the *disturbance function* are shown. The desired value represents the value it is desired that the control system reproduce, and it differs from the actual reference input by the characteristics of the reference input elements. The indirectly controlled quantity represents the quantity that is the actual system output. It differs from the controlled variable by the characteristics of the indirectly controlled system elements. The disturbance function represents an unwanted input to the system that tends to cause the controlled variable to differ from the reference input. The disturbance function elements shown by the dotted lines are intermediate between disturbance function and the controlled system itself. The dotted lines associated with the reference input and indirectly controlled system elements serve to indicate that these elements, when equal to unity, have a limited effect on the feedback control problem.

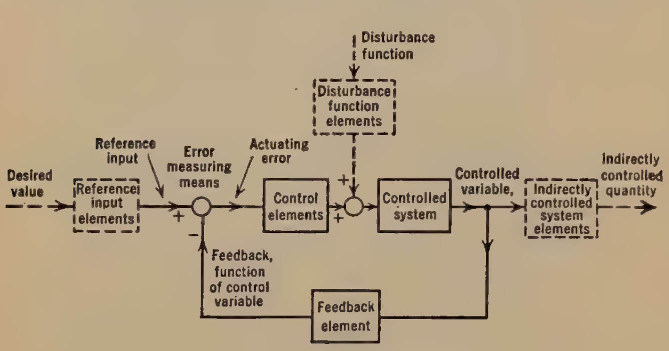

Fig. 1. Block diagram of simplified feedback control system

In many feedback control systems, the operation of all parts of the control system is continuous and automatic. By means of the continued use of the actuating error, such a feedback control system can be made accurate without requiring high accuracy or constant performance characteristics for all the control elements.

The principles of feedback control operation may be used effectively for any one of a number of different physical kinds of control problems, whether they employ electrical, mechanical, thermal, or other forms of control elements. Table I indicates some comm forms that these variables and elements take for a f types of feedback control systems.

Requirements of Stability and Accuracy

The basic principle of feedback control or close loop operation tends to make for accurate performan since the control system endeavors continually to cc rect any error that exists. However, this correcti action can give rise to a dangerous condition of u stable operation when used with control elements ha ing a large amount of amplification and significant d lays in their time of response.(10) An unstable contr system is one that is no longer effective in maintaini the controlled variable very nearly equal to the d sired value. Instead, large sustained oscillations erratic control of the controlled variable may take plac rendering the control useless.

If stable feedback control system performance is li that of a manually controlled system with a capab and well-trained operator, unstable feedback contr system performance may be compared to that of t manually controlled system with an untrained and responsible operator. Rapid and destructive respon of the system may result in which adequate control impossible, and destructive action of the controll variable may occur.

If, in an effort to increase the accuracy of the contr system, one increases the amplification of the contr without taking adequate steps to insure stable oper

TABLE I

LISTING OF VARIOUS FORMS OF FEEDBACK CONTROL SYSTEM QUANTITIES

Desired Value	Reference Input	Feedback	Error-measuring Means	Controlled Variable	Indirectl Controlle Quantit
Voltage	Potentiometer voltage	Voltage	Voltage detector	Terminal voltage	Load voltag
	Spring tension	Current	Galvanometer element		
Position	Angular shaft position	Angular shaft position	Differential gears	Machine tool position	Dimensions o metal being
	Electric field	Angular shaft position	Selsyn control transformer		
Temperature	Thermostat contact setting	Bimetal position	Bimetal thermostat	Oven temperature	Process temperature
	Potentiometer voltage	Thermoelectric voltage	Thermocouple		
Speed	Standard voltage	Voltage	Voltage detector	Governor speed	Alternat speed
	Calibrated spring position	Governor position	Linkage position		

›n, the advantages of the feedback control principle ove illusory. Furthermore, it is necessary to do more an have a system that is stable; one must have a stem that has an adequate margin of stability and n recover rapidly and smoothly from the shocks of egular inputs or of severe disturbances.

The requirements of stability and accuracy are utually incompatible. The higher the desired ac-racy, the smaller is the actuating error that can be lerated for proper corrective action, and the sooner ust full corrective action be initiated. Thus, to be curate, a system requires high amplification. How-er, with high amplification more corrective action of e controlled variable can take place for a given error, d the time during which the corrective action is re-ired is decreased.

Time delays in the various control elements and the ntrolled system that were not significant in a low-in system may become appreciable for the system th high amplification. After the corrective action is arted and the need for correction has ceased, the herent time delay of the system elements may prevent opping the action of the control elements in time to event an overshoot by the controlled variable. The ershoot may be greater than that which initiated e control motion, and the process of continued rrective action, building up to violent oscillations, is us started.

Following this line of reasoning, one sees that the me delays present in the control elements cause the stability. By appropriate use of "anticipation" eans to compensate for the inherent time "delays" the control elements, it is possible to obtain a high-in system with satisfactory stability. Although proved accuracy and adequate stability can be ob-ined, they are achieved only at the expense of addi-onal equipment or complexity.

athematical Basis for Stability

Essential and valuable as is the physical picture of ability, mathematical definitions provide more useful d exact means of describing system performance. e principal mathematical means for determining ability of linear control systems are the following:

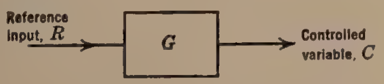

Fig. 2. Open-loop control system

(1). Locating by analytical or graphical means the tual position on the complex plane of each of the ots of the characteristic equation of the system

(2). Applying Routh's stability criterion(11) to the efficients of the system's characteristic equation

(3). Applying Nyquist's criterion(10) to a graphical ot of the open-loop response of the system as a func-n of frequency for a sinusoidal driving function.

The labor involved in locating the exact position of e roots of the characteristic equation or in calculating their values is such as to limit the use of this method. The Routh criterion involves the use of a brief, simple algebraic process and permits the ready determination of the system stability. However, the graphical data necessary for applying Nyquist's criterion provide quantitative information on the accuracy of the system, the degree of system stability, as well as the system stability itself. Hence it is the Nyquist stability criterion in one or more of its modified forms that is used most extensively to determine system stability.

The Nyquist stability criterion places on a firm mathematical basis the well-known physical fact that, when the feed-back signal to a control element is equal in magnitude and in phase with the actuating signal producing it, instability will result. Thus the Nyquist criterion establishes the necessary conditions for stability in terms of the ratio between the sinusoidal actuating signal and the feedback signal. The ratio is expressed by an amplitude and a phase relationship as a function of frequency. This ratio can be determined with the feedback not connected to the error-measuring element; thus the system need not be a closed-loop one under the conditions during which the stability as a feedback control system is evaluated. As such, the analysis of the problem is reduced somewhat in complexity, although the results are valid for the more complicated feedback control condition of system operation.

Features of Feedback Control System Performance

The two principal advantages of feedback control over control without feedback are that lower tolerances and greater time delays can be permitted for the control elements. To appreciate some of the advantages of the feedback control system, a comparison will be made between the open-loop and closed-loop (feedback) control systems. FIG. 2 and 3 are block diagrams showing how the controlled variable C is related to the reference input R for each of these two systems. The ratios of the controlled variable to the reference input for the open-loop and feedback control systems are, respectively,

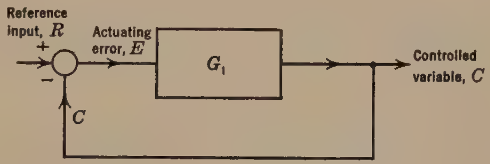

Fig. 3. Feedback control system with direct feedback

$$\frac{C}{R}=G \qquad (1)$$

and

$$\frac{C}{R}=\frac{G_1}{1+G_1} \qquad (2)$$

where $C/E=G_1$ and E is the actuating error.

The terms G and G_1 represent the transfer functions of the control elements. In addition to gain or constant terms, the transfer functions may contain time-functional relationships having a wide range of values from 0 to ∞ under varying input conditions.

In contrast with the feedback control system in which the controlled variable is compared directly to the reference input to provide the error signal that actuates the control system elements, the open-loop control system makes no direct comparison of these two variables. Thus it is assumed that the transfer function G is known and fixed so that the value of the controlled variable is known for each and every value of the reference input and its time variation. An example of this is a meter element; the deflection of the meter pointer is calibrated against a standard input—for example, a voltage. Subsequently it is assumed that the meter response is identical with its calibration figure and that the same input voltage will produce the same pointer deflection. However, a change in the characteristics of the transfer function G of the meter element may cause the same input to produce a value of output different from the calibrated value. The change in the value of the output, in terms of a change of the transfer function alone, is

$$\left.\begin{array}{l}\text{Change in}\\ \quad\text{controlled}\\ \quad\text{variable}\end{array}\right\} = \frac{\text{Change in } G}{\text{Proper value of } G} \times \left\{\begin{array}{l}\text{Proper value}\\ \quad\text{of controlled}\\ \quad\text{variable}\end{array}\right. \qquad (3)$$

From a knowledge of the value of the controlled variable alone, it is impossible to distinguish between a change in the reference input and a change in the transfer function. Thus very close tolerances in manufacture and constancy of controller characteristics with time are required to obtain high performance of an open-loop system.

For the closed-loop system there is less need for maintaining the transfer function constant, provided that the value of the transfer function G_1 is large. This may be seen from Equation (4), where the expression for the change in the value of the controlled variable in terms of its proper value and the transfer function G_1 of a feedback control system are shown.

$$\left.\begin{array}{l}\text{Change in}\\ \quad\text{controlled}\\ \quad\text{variable}\end{array}\right\} = \left(\frac{1}{1+G_1}\right)\frac{\text{Change in } G_1}{\text{Proper value of } G_1} \times \left\{\begin{array}{l}\text{Proper value}\\ \quad\text{of controlled}\\ \quad\text{variable}\end{array}\right. \qquad (4)$$

Although the change in the controlled variable is proportional to the change in the transfer function G_1, there is a greatly reduced multiplying factor of $1/1+G_1$ that decreases the size of the actual change in the controlled variable caused by changes in G_1. If G_1 has a value of the order of 10 or more, the advantages of feedback control operation in this respect are at once evident. Thus, even with the use of lower-precision components or ones subject to wider variation under use, it is still possible to maintain high-precision feedback control performance.

Two additional items are worthy of note in this brief comparison of open-loop and feedback control systems. First, it is not always physically possible to perforn direct comparison of the controlled variable to the ref ence input as shown in FIG. 3. For example, the ref ence input may contain *present* input data for a co puter that has as its controlled variable some functio relationship of the reference input such as the *futi* value of the controlled variable after some period time—for instance, T_f. Only by performing a duplica calculation or by allowing the time T_f to transpire is possible to know if the performance of the system seconds ago was correct. Thus it is clear that for certa control problems it is difficult to provide an erro sensing device that can compare the value of the co trolled variable to the reference input to modify t controlled variable properly.

Second, a feedback control system may be designed have the controlled variable very nearly equal to t reference input for only certain types of input signa For other signals the feedback control system m purposely be designed to make the controlled varial reproduce little or none of the input.[12] As an examp of this, position servomechanisms are frequently d signed to possess low band-pass characteristics. I this it is meant that reference input signals having lo frequency or constant values are transmitted witho appreciable error. The system transmission for highe frequency signals, which generally represent extraneo inputs, is purposely designed to be small, and the co trolled variable has a high error for this type of inp

FEEDBACK CONTROL SYSTEM DESIGN

As already pointed out, it is difficult to achieve bo a high accuracy and a high degree of stability in a fee back control system without increasing its complexi and cost. The design engineer continually balanc these factors in his effort to arrive at the system th will satisfy the job requirements. For this reason it important that the design engineer have availal methods of synthesis and analysis that make process of arriving close to the optimum design simple one.

Present-day methods of synthesis and analysis have ready gone far in satisfying this need. The work of bo Nyquist[10] and Bode[13] has been developed and tended. There are now available methods of synthe and analysis that remove much of the drudgery from t problem of servomechanism system design. The methods now make possible the synthesis of more co plex multiloop systems that hitherto have present an overwhelming analytical problem when only t more classical differential equation methods we available. With these design methods, the designer less burdened with laborious mathematical studies a is able to devote more of his time to understanding t physical principles involved in his problem. As a resu the control of more complex physical processes is ma possible.

A satisfactory feedback control system can now designed many times faster than was possible only few years ago. Complete systems need not always t up to arrive at optimum conditions by the "cut-ıd-try" process.(12) If it is necessary to determine some the parameters in this fashion, the number of ermutations and combinations is rapidly reduced by sing present-day methods of analysis as a guide. The esign engineer need no longer struggle with the soluon of a high-order differential equation to determine ie system characteristics. More important still, he eed no longer attempt to synthesize a servomechnism system by determining the effects of various pameter changes in the coefficients of the differential quation, and then the effects of the changes on these oefficients on the over-all system characteristics. It is uly a field, today, in which a practicing engineer can onfidently engage without being a highly trained athematician or an experienced cut-and-try experienter.

ecommended Design Procedure

In order for the practicing engineer to arrive at a edback control system design that best meets the quirements of a particular application, it is desirable at a general design procedure be available. Such a rocedure has grown up in the last few years. By using ie recommended procedure as a reminder of points to ieck, the engineer will arrive at a good common-sense esign that best meets the requirements of the job. ıch a design should be *reliable* in performance, *onomical* in cost and operation, *capable* of ready anufacture, *light* and *durable*, and easily *serviced.*

A suggested procedure in designing a feedback conol system is outlined below:

(1). Obtain a complete understanding of the job quirements

(2). Interpret these requirements in terms of such osed-loop design characteristics as frequency response ıd transient response

(3). Establish the approximate open-loop characristic that will satisfy the closed-loop requirements

(4). Determine the characteristics of the existing mponents that are a part of the job

(5). Select components, design amplifier and stabilizg circuits, and perform such other design requireents as to satisfy the necessary open-loop charactertics

(6). Refine the open-loop characteristics to gain rcuit simplicity and facilitate manufacture

(7). Check the design experimentally if possible.

It is of interest to examine each of these points in ore detail.

The importance of completely understanding the reirements of the job is often overlooked in the haste proceed with the more material aspects of the design. should be realized, however, that without proper formation regarding the job that the feedback control stem must perform, the final design may be over- or derdesigned. Complete information should always be tained on such important characteristics as the reired speed of response, smoothness of operation, duty cycle, power-supply stability, operating temperatures, allowable errors, and types of input motion or load disturbances.

Having acquired this information from the customer, the designer must, as a first step, interpret it in terms of the customary performance characteristics of the servomechanism system. If the customer has not already given definite information on the frequency response or transient response, these requirements must be interpreted from the data that the customer does have available.(14) The designer should know as a function of frequency the *allowable* characteristics for $\frac{\text{error}}{\text{reference}}$, $\frac{\text{controlled variable}}{\text{reference}}$, and $\frac{\text{controlled variable}}{\text{load disturbance}}$ if he is to make a good design. After having made this interpretation of the customer's problem, the designer should have a clear conception of the closed-loop characteristics that the system must exhibit, and he should be in a position to proceed with the determination of the open-loop characteristics.

The most direct path in design is to decide what is required and then to proceed to design the device directly from these requirements. This often has not been possible in servomechanism design, because there was no path to establish the system parameters directly from the closed-loop characteristics. Instead, extremely time-consuming cut-and-try methods were used. In more recent years the complex plane plots and attenuation-phase diagrams(15),(16) have greatly reduced use of the cut-and-try process but have not completely eliminated it.

In an effort to reduce further the use of the cut-and-try process, a series of charts has been made available(17) that make it possible for the servomechanism design engineer to go directly from the desired closed-loop frequency or transient response to the open-loop attenuation diagram. In this way the gap between the closed-loop and open-loop characteristics is considerably shortened. Later in the design it may be necessary to refine the open-loop characteristic to fit the requirements of the problem more exactly.

For a new system in which the motors or other control elements are not yet established, the next logical step is to choose devices such as generators, motors, or other power elements that have the proper dynamic characteristics to satisfy the open-loop characteristic without the need of additional feedback to improve their dynamic response.(18) However, many times the requirements are such that additional feedback about the output devices will be required to improve their speed of response. Frequently, because of economic considerations, the servomechanism designer will find that he has the problem of using a control element whose dynamic properties are somewhat inadequate for the job. It is then the task of the designer to modify the dynamic properties of this element as best he can and to make the best compromises in the open-loop response so as to meet most nearly the closed-loop response.

Before the designer can modify the dynamic response of these already existent components, he must, of course, know their dynamic properties. Thus, if such components already exist in the system, the designer should proceed to obtain their characteristics before attempting to synthesize the open-loop characteristic. It is here that, many times, certain measurement techniques prove to be very useful in saving time in determining the characteristics of the devices.(19)

Having the characteristics of the output devices and the desired open-loop response, the designer is then in a position to select the circuit components and design the amplifiers and other elements required to meet the open-loop characteristics. Charts have been compiled that make it possible to select the desired network configuration after its transfer function has been determined from the open-loop characteristic.(20) Both a-c and d-c amplifier design are well treated in the current literature.(21),(22) However, there are certain aspects of amplifier design such as "drift" and change of "stage gain" as a result of tube aging, power-supply variations, and other factors that are of great importance to the servomechanism design engineer.

In many instances, before the design is frozen it may be necessary to make further refinements. From a practical design standpoint it may be found that considerable circuit simplification can be achieved by slight modifications of the network transfer functions. If this is done, it may be necessary to refine the open-loop characteristics to include the change. One example of this is the use of feedback circuits to achieve transfer functions similar to simple series circuit elements but using smaller components.

After the design is completed, it is important that it be checked experimentally if possible. Such a check is valuable for two reasons. First, it guarantees the customer receipt of a system that meets his specifications; second, it provides the engineer with valuable experience for use in his future designs if the check should reveal errors. Many experimental techniques have been devised to measure the closed-loop characteristics of the final system as a check on design.

DEVELOPMENT OF THE FIELD OF FEEDBACK CONTROL SYSTEM

Regulator and *servomechanism* are terms that have been applied to feedback control systems. Although equipments of the two types may be similar if not identical in their physical appearance, the difference in name arises primarily from the different nature of the types of inputs and disturbances to which the control is subjected and from the number of integrating elements in the control. The close functional similarity of these two types of control systems has resulted in their recently being given the common title of feedback control systems.

The regulator is a type of device long used in many different forms in the central-station and industrial-control fields to regulate such quantities as power system voltages, paper drive speeds, or roll tension in winding applications.(23),(6) Regulators are designe primarily to maintain the controlled variable or syste output very nearly equal to a desired value, at whic it is to be regulated despite fluctuations of the loa on the output. Although occasionally it is necessar to maintain control of the output as the desired valu is varied over a range of values, this is not the princip feature of regulator operation. Generally a regulat does not contain any integrating elements.

The term servomechanism is more recent, appa ently being first used in an outstanding paper by H. L Hazen(24) in which, in 1934, he set forth a detaile analysis of on-off and continuous-control servomecha nisms for position control. The major emphasis in tha paper, and in many other servomechanism application after that time,(25),(26),(27) was on the design of a co trol capable of producing a controlled output positio very nearly equal to a reference input position, whic in general is a simple function of time. The effect load fluctuations and other disturbances was general not of major importance in this type of system an was given less emphasis in the servomechanism desig Generally one or more integrating elements are co tained in the forward transfer function of a serv mechanism system.

Many of the military applications required durin the first World War indicated the desirability of rapi accurate, and automatic control of position for suc applications as remote indicators and power drives fo moving heavy loads. Early developments of conside able importance in this field of servomechanisms du ing the 1920's were automatic controls for steerin ships and for positioning naval guns on shipboar Minorsky's work in providing automatically controlle ship steering is a classic in the development of serv mechanisms.(28),(29)

Because of the understandable necessity for milita secrecy in much of the development in the field position controls, and because of the somewhat differen design emphasis on regulator and servomechanis applications, it is not suprising that the similarity these two phases of the control problem was n emphasized and exploited more fully. Although durin the second World War there was little exchange of i formation between the servomechanism and regulat design engineers, since 1945 there has been a health exchange of ideas.

Early designers in the field of feedback control sy tems made almost exclusive use of the differentia equation method of problem analysis, for it aided the intuition and gave them a physical picture of the r quirements of the control system. The work of Mino sky and Hazen makes use of the differential-equatio approach. Later this differential-equation, or *transien* approach was greatly extended by Brown, Hall,(and others, to provide general nondimensionaliz information(31),(32) concerning servomechanism respon and design methods for the simpler control system The use of the Laplace transform was found to advantageous for this work. Although still used e nsively, the transient method of analysis has been enerally supplanted by the *steady-state* sinusoidal nalysis and synthesis methods.

In the early 1930's, work in the seemingly unrelated eld of feedback amplifier design by Nyquist(10) and lack(33) brought about the development of the theory the stability of closed-loop systems on the basis of e system open-loop response to steady-state sinusoidal citation. This basic concept provided data upon which ter developments were made to provide the modern chniques of feedback control design, which are based pon steady-state response characteristics. Bode, in 938,(13) showed the intimate relationship between the tenuation frequency and phase characteristics of inimum-phase electrical networks, a relationship ter used for the more general control problems.

The impetus of military demands for automatic ontrols in the second World War permitted concentraon of a large amount of effort in the field of servoechanisms. Tremendous strides were made during is period in extending the design and analysis techiques as well as in the construction and operation of astly improved feedback control systems.

Harris in, 1941,(26) and Hall, in 1943,(27) illustrated ow the complex-plane approach of Nyquist could be sed for purposes of servomechanism design and nalysis. In addition, these men provided a most useful terpretation of the various vectors on the complex lane in terms of their physical significance as part of e servomechanism problem. During the years 1941 to 945, Bomberger and Weber,(34) MacColl,(35) Nichols,(15) ode,(36) and others(37) indicated how Bode's attenation-phase concepts could be applied to the servoechanism design problem to provide a more direct ethod of servo system analysis and synthesis. The fects of the extraneous inputs (noise) on servomechaism performance and design were considered by Weiner, hillips,(15) Hall, and others during this same period. n effort was made to establish criteria for the "optium" servomechanism performance under the condion of combined signal and noise inputs to a servoechanism.

Of comparable importance to the development of nalytical tools for solving feedback-control analysis nd synthesis problems was the development of imoved power sources, error indicators, and other comnents for supplying the practical needs of the servoechanism designer. Typical of these are such devices the amplidyne for obtaining a high-gain rapid-sponse d-c generator,(38),(39) the selsyn generator-ntrol transformer for supplying an electric signal oportional to rotational error,(40) and a number of draulic pumps, motors, and amplifier units for urces of power and control.

Since the end of the second World War a great deal the control system information developed during e war has been published in books(15),(16),(35),(41),(42),),(44) and articles that have materially aided the wideread development and use of servomechanism design ethods. At present, general servomechanism concepts are being used in many applications previously considered to be regulator problems. Gradually, under the leadership of such men as Brown, Herwald, Crever, and Ahrendt, an effort has been made to draw the fields of regulator and servomechanism design together under the more inclusive heading, feedback control systems. Under the stimulus of the postwar demand for goods, faster and more accurate industrial controls are being designed and built to utilize components developed in wartime. Steel- and paper-mill drives and machine-tool controls are representative of such applications.(23),(6) Simple position-control servomechanisms are being used in more complicated control systems for guided missile and other intricate applications.

Recent progress in servomechanism applications has been great, but large segments of engineering activity remain available for future development. Without question, automatic feedback controls have become an important and integral part of the modern manufacturing and industrial processes. Automatic flight control and military applications of automatic control are being further extended.(45),(46) Already somewhat automatically controlled, the chemical process-control industries will become more completely automatic in the future, as refined measuring means are developed. More widespread use of simple computers for providing means of completing the feedback control loop will permit more fully automatic operation of comprehensive control problems.(1)

In the field of analytical development, the future will doubtless see greater understanding and use of nonlinear control elements. If possible, the present highly developed linear theory will be extended to permit rapid and accurate analysis of servomechanism systems with such unavoidable nonlinearities as saturation and backlash. The work of Kochenburger(47) is an important step in this direction. Although the use of such aids as simulators(48) and analogue and digital computers(49),(50) at present permits the analysis and synthesis of nonlinear servomechanisms, it is hoped that simpler, less expensive ways may be made available for handling this type of design problem in the near future.

In addition there doubtless will be improvements in the components and equipment that make up the feedback control system. Smaller, more accurate, and reliable error- and rate-measuring devices as well as greater power and lighter, faster control elements are representative of the component advances that should be made in the future.

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HIGH LIGHTS AND SIDE LIGHTS

Heating Cable Keeps Runways Free of Snow

Concrete crane and transport runways at a Midwestern industrial plant are being kept clear of snow by application of heating cable. Just before the worst part of the winter last year, the company lined the runways with flexible lead-covered heating cable. The installation, comprising 40,000 ft of cable, covers four concrete runways ranging from 100 to 275 ft in length and about ten feet wide.

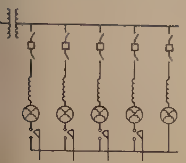
Step-down transformers, to supply correct voltage for the nonstandard lengths of heating cable, were built especially for this installation. This required secondary voltage is about 180 volts for the shortest runway and about 500 volts for the longest. The heating cable is laid on wire mats about 2½ to 3 inches below the surface and on approximately 3-in. centers. Tile drains installed along the edges of the runways provide adequate drainage for the melted snow.

In its greatest test to date last winter after a week-end snowfall, with the outside temperature at eleven degrees below zero, the heating cable was able to clear the runways in a few hours.

Concrete runways are being kept clear of winter's worst blasts by means of a novel application of heating cable

BUS AND INDIVIDUAL FEEDER REGULATION

actors to be considered in selection of the ethod of voltage regulation best suited to a iven application, residential or industrial



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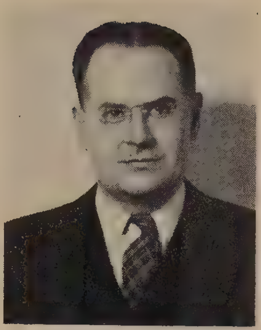


E. M. Hunter

D R Samson

THE regulation of feeder voltage by means of a voltage regulator is primarily a distribution probem. Those engineers familiar with the complexities of roviding adequate consumer voltage will readily agree hat the ultimate in voltage control can be obtained rith individual feeder regulation, but it is not sound ngineering to arbitrarily recommend single-phase egulation to the exclusion of three-phase regulation. In eneral, the two major considerations involved in a decion between bus and individual feeder regulation are:

(1). The quality of regulation to be obtained
(2). The economic considerations involved.

QUALITY OF VOLTAGE REGULATION

The tolerable voltage conditions for the ultimate sers' requirements, for a given feeder, or even a group f feeders, are dictated by the operating characteristics f the consumer's equipment. The actual maximum r minimum voltage conditions allowed on a feeder or o a customer are usually well within these tolerable mits. These maximums and minimums are set by tate Public Utility Commissions or the utility management, engineering, or operating divisions. The ultimate im in a voltage-regulator application is to maintain t the terminals of the utilization equipment a relatively onstant and correct voltage level. How well this aim f relatively constant and correct voltage level is ulfilled is in reality a measure of the quality of voltage egulation. It may be emphasized that the quality of oltage regulation is dependent upon the method of egulation, the regulator band width, and the regulaor's control accuracy.

lethods of Voltage Regulation

In the distribution area, the methods of regulating oltage by means of voltage regulators are commonly assified as:

(a). Bus regulation, usually three-phase
(b). Individual feeder regulation, three-phase or single-phase
(c). Supplementary regulation, usually single-phase

Bus regulation controls or holds the voltage of a bus r common terminal of two or more feeders within redetermined voltage limits. Present practice is predominantly three-phase bus regulation, although single-phase bus regulation has been and still is used by a few system operators. The voltage control signal for bus regulation is usually taken from one of the phases or, in certain instances, an average of the three phases. Thus three-phase bus regulation simultaneously holds voltage maximum and minimum limits to coincide with the controlling phase, regardless of the requirements of the other two phases. The quality of regulation on any particular phase of a feeder becomes dependent upon how closely its requirements match those of the controlling phase.

Various methods have been derived to improve the quality of voltage held with bus type of regulation. Feeders of like characteristics are connected to the same bus section. Sometimes feeders of approximately equal express runs or with equal distances to the first consumer are connected to the same bus section. Obviously, the ultimate in this type of regulation is connecting one feeder to a regulated bus. This then becomes three-phase feeder regulation.

Individual feeder regulation holds the voltage of only one feeder within predetermined voltage limits. This type of regulation may be either three-phase or single-phase. Single-phase feeder regulation provides the maximum application flexibility, since each phase is individually controlled and the effects of unbalanced loads between phases or unequal express feeder length can be minimized with this type of regulation.

Supplementary regulation consists of any regulation located on the feeder remote from the substation. This type of regulation is also commonly referred to as branch feeder regulation. As the name implies, this method is used to supplement any of the previously mentioned types of regulation when either load or distance results in unacceptable voltage at or near the load end of the feeder.

Bus Regulation

Primary network applications are particularly well served by bus regulation. Automatic load-ratio control in the transformer is most commonly used for this application with factory-assembled substations. A one-line diagram of a typical substation is shown in FIG. 1. The under-load tap-changing equipment provides adjustment of the secondary voltage of the transformer over a range of 20 percent in ⅝-percent steps, to compensate for variations in supply voltage and for line drop in the primary feeder lines at various loads.

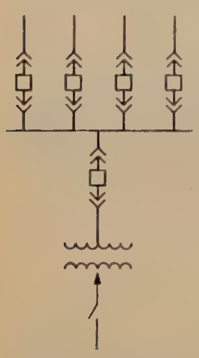
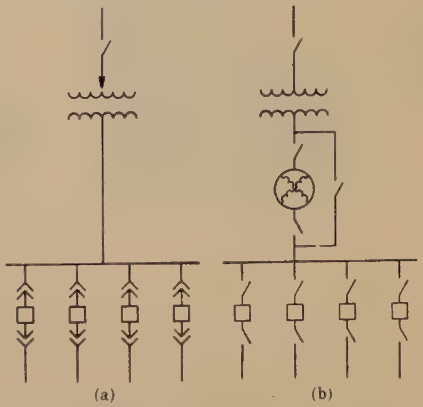


Fig. 1. Typical substation arrangement for a primary network



(a) (b)

Fig. 2. Substation arrangements for radial system: (*a*) load-ratio control; (*b*) induction regulators

Bus regulation is also often acceptable for a simple radial substation, as shown with load-ratio control or induction regulators in Figs. 2(a) and 2(b). To be reasonably acceptable, all feeders should be of about the same length and have loads and peaks which coincide. If these conditions are not met, a compromise in the voltage maintained on each feeder must be made. Such compromises, although objectionable, are often tolerated on the types of loads usually supplied by relatively small substations of the radial type. The use of bus regulation for larger stations should be more critically examined, as the obvious saving in substation costs may unsuspectingly be more than overbalanced by additional costs required in the distribution systems to keep voltage within acceptable limits.

Where industrial and residential loads are to be served from the same substation, bus regulation has been adapted by installing two or more separately regulated bus sections, as shown in Fig. 3. Feeders of similar characteristics with regard to length and load are grouped on one bus, and those of other similar characteristics on another. This obviously permits regulation more nearly matching that required on each feeder. During normal operation, industrial loads that might cause objectionable voltage flicker can
segregated from the domestic load. This type of regul
tion is referred to as group feeder regulation.

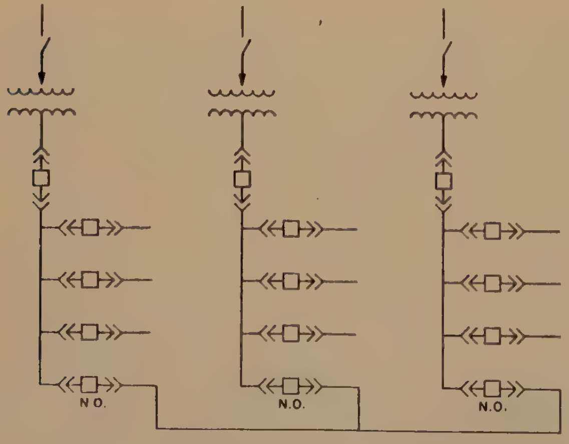


Fig. 3. Three-unit substation located on the same piece of land

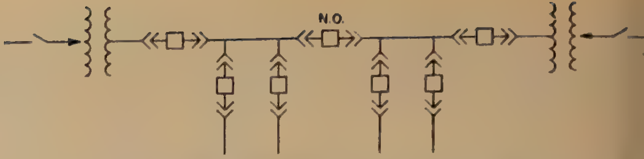


Fig. 4. Low-voltage selective substation arrangement

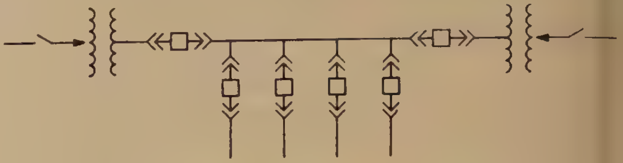


Fig. 5. Spot-network substation arrangement

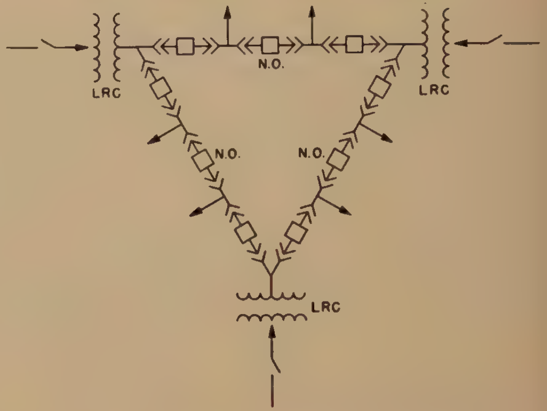


Fig. 6. Multiplex substation arrangement

Under emergency conditions, one transformer
high-line circuit may be out of service, and durin
such periods both types of loads can be carried fro
one bus. Under these emergency conditions, the vol
age held is a compromise. In general, it appears th
most voltage-regulating problems are engineered
hold acceptable voltage under normal conditions, ar
under emergency conditions the prime objective is
maintain service continuity. This is justifiable becau
most emergencies of this sort are of relatively sho
duration.

Other types of substations that provide bus regul
tion are the low-voltage selective (Fig. 4), the sp
network (Fig. 5), and the multiplex (Fig. 6). With th
exception of the spot network the voltage-regulati
limitations of these substations under emergency co
ditions are similar to those for the substation wi
group feeder regulation.

Individual Feeder Regulation

Individual feeder regulation is a refinement of b
regulation and, in general, gives better voltage contr
since the requirements of the feeder alone need be co
sidered. Substations which provide individual feed
regulation are:

(1). Single-feeder substations
(2). Duplex substations
(3). Regulator-reactor-transfer bus substations.

The single-feeder substation is shown in FIGS. 7(a) l 7(b). Either a load-ratio-control transformer or a oarate regulator may be used. Usually such sub-tions are used in an open-network system. An open-twork system refers to radial sections of systems th normally open tie switches located in the streets. the event of a substation outage, the substation d is carried on an adjacent feeder and substation closing the tie switch.

In some applications, the open-network system is ither available nor acceptable for the service to be idered, but individual feeder regulation is still ssible with the duplex substation, as shown in G. 8. Each of the two transformers normally supplies d regulates a feeder. Under emergency conditions, e two feeders are connected together automatically ien loss of voltage occurs on either transformer. This plex arrangement provides individual feeder regula-n under normal operation, immediate restoration of vice in case of high-line or transformer trouble, and eans for isolating the transformer and regulating uipment and the feeder breakers, for maintenance, th all of the switching done with adequate power cuit breakers.

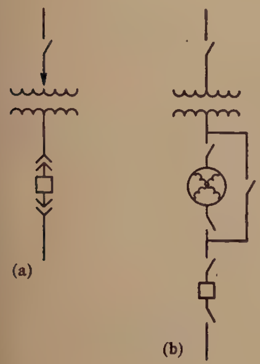


Fig. 7. Single-feeder substations: (*a*) load-ratio control; (*b*) separate regulator

The most conventional manner of supplying individ-l feeder regulation is by the arrangement shown in G. 9. The substation consists of a regulator, either ee-phase or three single-phase, together with a nsfer bus and by-pass facilities for either the regula-or the feeder breaker for each feeder position. actors are sometimes supplied when the short circuit n excess of the regulator capabilities.

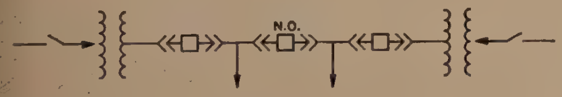


Fig. 8. Duplex substation arrangement

f, in the arrangement of FIG. 9, single-phase or plex regulators with individual phase control are d, regulation is provided to permit control of each ise individually. This is the control used when the ds are predominantly single-phase and the "phase-a" system of distribution is used. With the trend more and more three-phase loads on distribution tems, use of phase-area distribution is diminishing.

Regulator Band Width

As stated previously, the quality of regulation is also dependent upon the band width of the voltage-regulating relay. The term "band width" is generally assumed, in the industry, to be the difference between the voltage limits which the voltage-regulating relay is set to hold. Certain factors tend to cause the voltage to exceed the band width as thus defined, such as:

(1). Time delay in the regulator-control circuit
(2). Mechanical operating characteristics of the regulator.

These factors are beyond the control of the voltage-regulating relay. As stated previously, the effects of these factors are to cause the voltage to exceed the band limits. Thus, the difference between the voltage limits which are actually held at the output terminals of the regulator is referred to as the "effective band width."

If a regulator had instantaneous response to the dictates of the voltage-regulating relay (about 0.1 sec for the induction-type regulator) and if the regulator were not restricted by mechanical operating characteristics, the effective band width (the voltage spread actually held at the terminals of the regulator) would be equal to the band setting of its voltage-regulating relay. Conversely, if a regulator did not attempt to correct voltage variations outside of those limits set by the voltage-regulating relay until such variations persisted for a specified length of time (1 hr, 1 min, or 1 sec), then the voltage limits at the terminals of the regulator would definitely exceed the limits set by the relay. Thus, the inherent and necessary time delay (adjustable for 3 to 120 sec) in the control circuit of the step-type regulator tends to widen the effective band width. This is shown diagrammatically in FIG. 10.

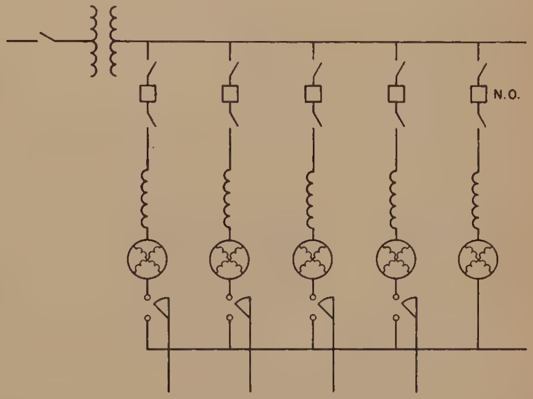


Fig. 9. Individual feeder regulating arrangement with regulator-reactor transfer bus

There are obviously specific circuit conditions under which the quick response of a regulator to a fluctuating input voltage will merely amplify the voltage trouble. The addition of time control under these circumstances may prove more advantageous than widening the band-width setting of the voltage-regulating relay. However, such applications are the exception rather than the rule.

Control Accuracy

The control accuracy of a regulator has an effect upon the regulator output voltage which is very much analogous to that of time delay. Industry standards classify control device accuracy as:

Class 1, ±1 percent over-all error
Class 2, ±2 percent over-all error
Class 5, ±5 percent over-all error

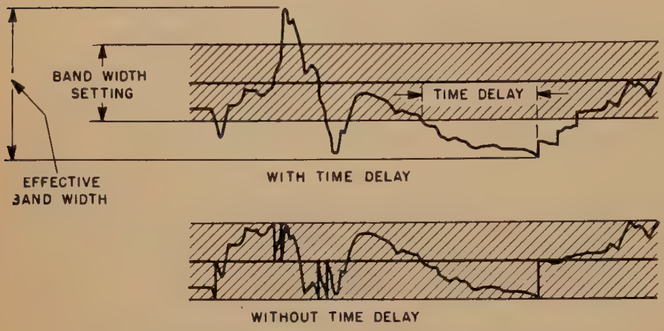


Fig. 10. Effect of time delay on regulator band width

The errors referred to under these classes are composite effects of temperature and frequency on the control-equipment components, necessary tolerances in the potential-transformer ratio, and errors occurring in compensator impedance elements. These errors do not affect the band width, but they do cause the voltage level held by the voltage-regulating relay to vary. As an example, a voltage-regulating relay may be adjusted to hold 120 volts (in secondary terms) with a ±1-volt band width. A change in the ambient temperature may cause the relay to hold a voltage other than 120 volts, but the band-width adjustment will remain one volt above and one volt below this new voltage level held by the voltage-regulating relay. In general, the factors which affect control accuracy are not transient in nature, as is the case with time delay. In certain localities a given temperature change may require several months, and in another locality it may require only a matter of weeks or days to experience the same temperature change. Thus it is entirely feasible for regulator to hold an average voltage level other tha the desired 120-volt setting for a considerable peric of time. Indeed, the quality of voltage regulation dependent upon the method of regulation, the highe possible control accuracy, and a narrow band-widt setting of the voltage-regulating relay co-ordinate with the proper selection of time delay.

ECONOMIC CONSIDERATIONS

In a consideration of the economic aspects of distr bution-system regulation, the problem involves initia investment installation and maintenance costs, lo evaluation, and comparison with other methods regulation including the expense of transfer bus, et Many of the economic considerations are studied on a individual basis, comparing various alternatives. Hov ever, a few of the economic considerations can generalized upon.

A comparison of initial investment for some of tl various types of regulators is shown in Fig. 11. Obv ously, single-phase regulation is more expensive for tl higher current capacities than three-phase feeder reg lation. In addition, a certain percentage of the feeder load-carrying ability will be restricted with three-pha regulation if the phase loading does not remain balance and coincidental, or if the express portions of eac phase are not equal. This, too, has a dollar valu Whether it can be claimed now or at some future da is determined by present and future circuit conditior A monetary value should also be placed upon tl effects which band width, time delay, and contr accuracy will have on the feeder's load-carrying abilit Figs. 12 and 13 show the effects of reduction in bar width on the load-carrying ability and permissib length of a feeder when limited by load-area volta drop. These curves are equally applicable to any r duction in the variation of output voltage which m be obtained by increased control accuracy.

The effects of unbalanced loading between phas

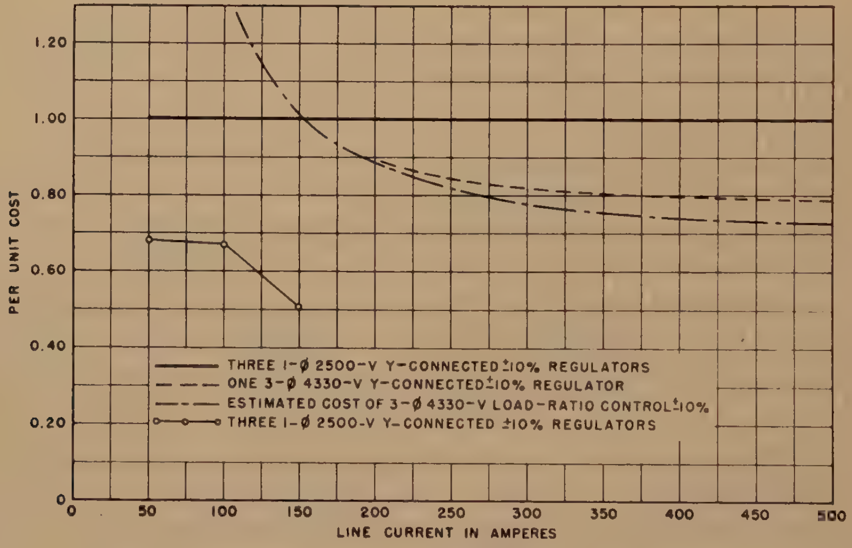
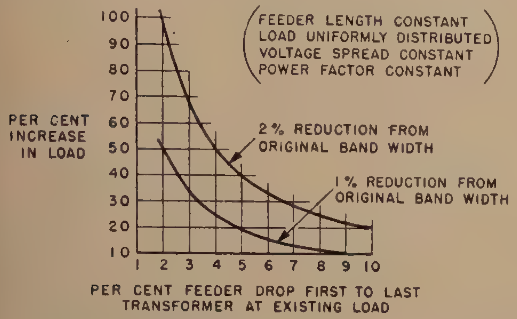


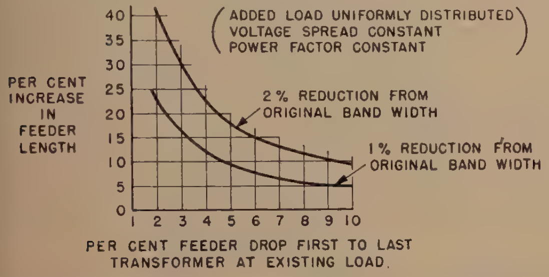
Fig. 11. Comparison of initial investments for four types of regulators

d sometimes between feeders may be overcome by e use of additional supplementary regulation. From G. 11 it can be seen that the cost of supplementary gulation is lower than that of other regulators. It ould also be noted there are savings to be had in the tial investment with regulation which is physically corporated in the station transformer (load-ratio ntrol). This, of course, is applicable only for bus and ssibly three-phase feeder types of regulation.

The losses of the various types of single-phase regu- ors are about the same. The three-phase regulator s slightly lower losses than three equivalent single-phase regulators, and this has a definite dollar-and-cent value. Obviously, this dollar difference is dependent upon load factor, energy and demand charges, etc.



ig. 12. Permissible increase in feeder load for a decrease in band width



. 13. Permissible increase in feeder length for a decrease in band width

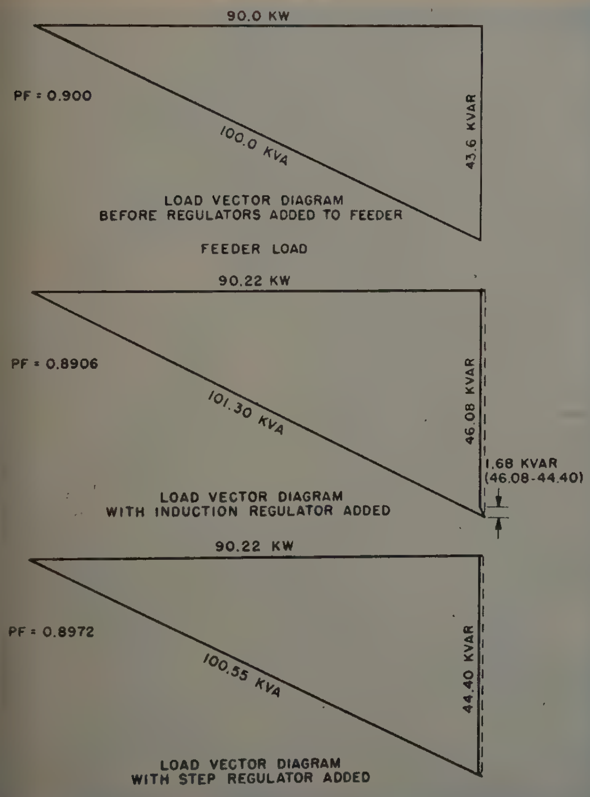

90.0 KW
PF = 0.900
100.0 KVA
43.6 KVAR
LOAD VECTOR DIAGRAM BEFORE REGULATORS ADDED TO FEEDER
FEEDER LOAD
90.22 KW
PF = 0.8906
101.30 KVA
46.08 KVAR
1.68 KVAR (46.08-44.40)
LOAD VECTOR DIAGRAM WITH INDUCTION REGULATOR ADDED
90.22 KW
PF = 0.8972
100.55 KVA
44.40 KVAR
LOAD VECTOR DIAGRAM WITH STEP REGULATOR ADDED

Fig. 14. Effect of regulators in neutral position upon feeder load

Occasionally the exciting currents of the step and induction regulators are economically compared. The induction regulator has an inherently higher exciting current than does the equivalent step machine. This, of course, is due to the presence of an air gap in the magnetic path of the induction regulator. This evaluation is usually based upon the amount of capacitive kva necessary to compensate for the difference in the required reactive kva of the two regulators. The difference in reactive kva is only a part of the true comparison; the no-load and full-load losses should also be compared. It is quite possible for the regulator with the higher exciting current to have the lower losses. Hence, the evaluation of these losses should be included in any economic comparison. Fig. 14 shows a comparison between the induction and step regulators. Although the losses are shown equal in this example, the method of comparing the kw losses will be analogous to that for exciting kvar.

SUMMARY

There are numerous complexities to be faced in selecting a method of regulation in many applications. Although there is no single cut-and-dried formula, there are several general bench marks to be noted.

(1). Bus regulation is applicable when the substation is located near the load area, the feeders are approximately equal in length, the feeder and phase loads are balanced, and the load cycles are coincidental

(2). Three-phase feeder regulation, like bus regulation, requires balanced and coincidental phase loads. However, three-phase feeder regulation does not require the same proximity to the load area as does bus regulation

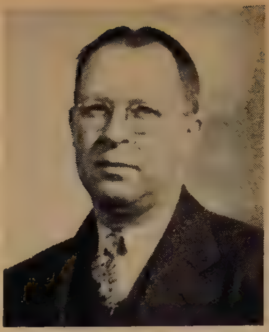
(3). Individual or single-phase regulation, although applicable to most circumstances, is used most frequently in circuits where loads are predominantly single-phase or the express runs long and unequal. While single-phase regulation may require a greater initial equipment investment, its ability to correct unbalanced voltage conditions and its flexibility in future applications often makes individual phase regulation the most economical method of regulation.

Present trends indicate an increasing number of three-phase regulation applications, principally bus. This is a result of increasing three-phase loads, closer balancing of feeder loads, and the use of unit substations out in the center of the load area. Also, as load density grows and new substations are located in the load area, it becomes easier to hold adequate consumer voltage with bus regulation. The availability of supplementary regulation and shunt capacitors has encouraged the use of bus regulation by providing additional regulation or voltage boosts for both unexpected and anticipated undesirable voltage conditions.

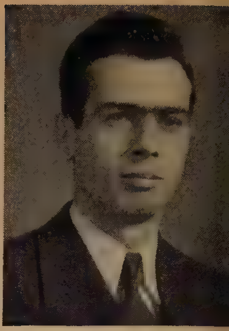
PYROMETER MILLIVOLTMETER AND AUTOMATIC CONTROLLER

A new electrical indicating instrument and automatic controller designed primarily for temperature applications in ranges varying from 0-300 F to 0-3000 F

By E. W. CLARK and J. K. SIDEBOTTOM
Meter and Instrument Department
General Electric Company



Earl W. Clark



Joseph K. Sideb

IN MANY industries, the measurement and automatic control of temperature is a function of critical importance. The two most common types of equipment for effecting such measurement and control employ (1) a potentiometer circuit or (2) a highly sensitive millivoltmeter to measure the voltage output of a thermocouple, and to initiate consequent control operations. Although the potentiometer-type device is superior in accuracy, this feature is offset by its high cost and mechanical complexity; and hence, for many applications, the millivoltmeter equipment is preferred. This article describes the design of a new pyrometer millivoltmeter and its associated control units in which modern materials and techniques have been used to fullest advantage to produce an instrument of guaranteed accuracy, outstanding in simplicity, reliability, sturdiness, and low cost.

The major components of the new millivoltmeter and their functional relationship to one another, and to the temperature-measuring system as a whole, are shown in the block diagram in FIG. 1. The thermocouple is a separate device, the output voltage of which is measured by the millivoltmeter. The control operation is initiated by a small aluminum vane fixed to the instrument pointer. As the measured temperature varies, the vane moves into and out of the space between two high-frequency sensing coils, thus varying the current in the oscillator circuit and, ultimately, through a series of relays, operating a contact to control the temperature.

For automatic control, internal contactors are us which permit direct control of either one or two circu rated up to 10 amperes at 120/240 volts if mechani contactors are used, or rated 35/25 amperes if mercu contacts are used. The instrument or controller may modified to operate with any primary detector whi provides a voltage output of 10 millivolts, or high at 48 microamperes.

Just as, functionally, the controlling pyrometer m be broken down into two parts, namely, an accura measuring device and an automatic controller, so t the problem of its design may be subdivided into t problems: measurement and control.

The Measurement Problem

From the user's viewpoint, the most importa requirements for a measuring device are accuracy a reliability. An instrument must consistently give t correct value of the quantity measured. Other fact which must be considered include readability, size, a pearance, durability, and cost.

The permanent-magnet moving-coil instrument h over many years, been one of the simplest, most a curate and most reliable of d-c measuring instrumen The new millivoltmeter is, therefore, an adaptation this basic measurement mechanism (FIG. 2). A vari of temperature ranges from 0–300 F to 0–3000 F a made possible by designing the instrument in vari ratings up to 70 millivolts.

One of the major problems encountered in design a measuring mechanism suitable for the pyrome

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Presented at the Fall Meeting of the American Society of Mechanical Engineers, Minneapolis (Minn.), September 26–28, 1951.—EDITOR.

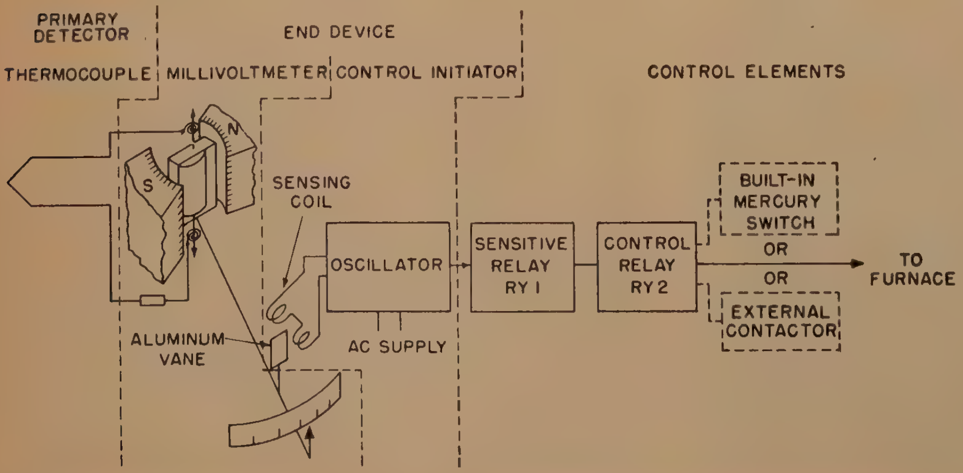
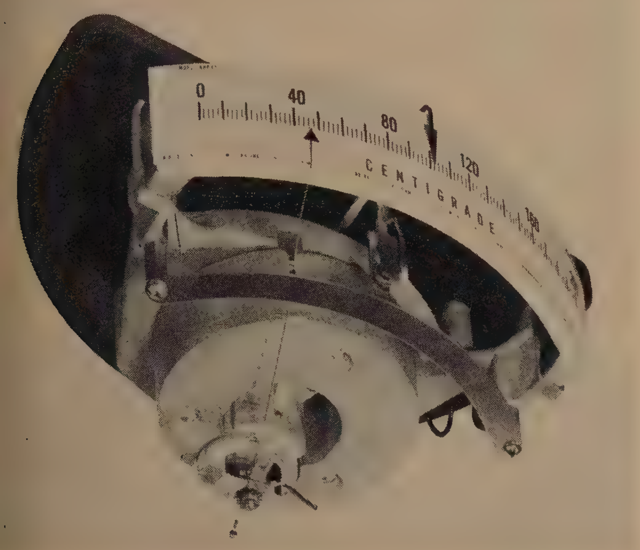


Fig. 1. Components of pyrometer millivoltmeter and automatic controller shown in functional relationship to temperature measurement and control system

plication is that of securing adequate torque at low ergy levels, since, for certain ratings, the power availle for full-scale indication is as little as 0.5 microwatt.

In a permanent-magnet moving-coil instrument, the flecting torque is directly proportional to the magtic flux density in the air gap. An excellent material such a magnet is alnico V which, however, requires ecial directionalizing techniques in order to realize full potentialities. These techniques have been carelly developed for the instrument under consideration d applied to a properly proportioned magnet of nerous size. Consequently, the air-gap flux density is nsiderably higher than that in other instruments of is type. Clearances of 0.062 in. have been provided the moving coil which precludes jamming of the



. 2. Basic measurement mechanism of pyrometer millivoltmeter and omatic controller, showing sensing coils and actuator vane

l due to particles accidentally lodged in the air gap other causes. The high flux density thus obtained gives uperior value of torque and robust performance even the low energy levels furnished by the thermocouple.

Another important consideration in instrument sign is that of maintaining a sufficiently high factor of rit(1)—that is, the relationship between the torque T the instrument and the weight W of its moving stem, $\frac{T}{W^{1.5}}$. Since, as pointed out previously, the erating torques available are low, it is desirable to luce the weight of the moving system to an absolute nimum. This is accomplished largely through a ique method of winding the coil and reducing the e of parts to a minimum consistent with performance quirements. The high sensitivity control current perts the use of a very lightweight (14 milligrams) uating vane, thereby keeping the over-all weight of moving system at a minimum. In all, the weight of moving system of the new instrument totals apximately one gram—a two-to-one saving over most rmanent-magnet moving-coil instruments of comparable size. Instrument bearing friction(2) is kept within close tolerances by quality control. Spring-mounted jewels are employed to prevent shock damage to the bearing system. A standard 50g shock test repeated ten times in each of three planes produces a change in reading of less than 0.1 percent of full scale.

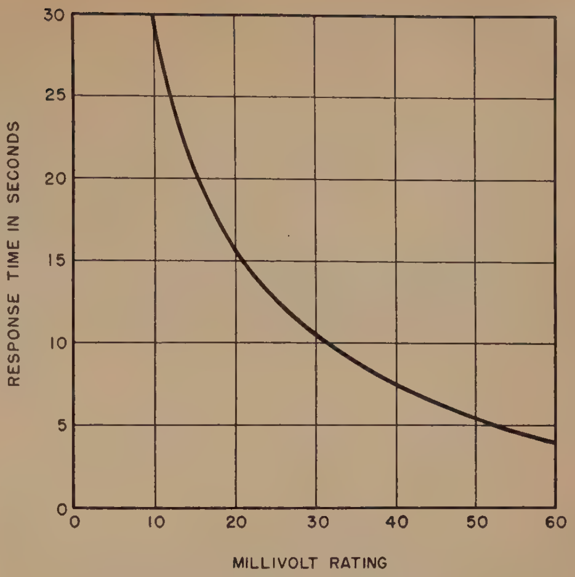


Fig. 3. Average responses of millivoltmeter connected with thermocouple. Curve shows time required to travel from zero position to full scale and remain within ½ percent of full scale when full scale voltage is suddenly applied

Because of the low weight and inertia of its moving system, the undamped period of the millivoltmeter is approximately 4½ seconds. Inasmuch as virtually all damping is obtained from the coil and loop-circuit resistance, the response time varies with the instrument rating. Response time is here defined as the time required for the pointer to travel from zero position to full-scale and remain within ½ percent of full-scale when full-scale voltage is suddenly applied—that is, the time between the application of full-scale voltage and the instant when the pointer oscillations decrease to within ½ percent of the full-scale rating. Average responses of the millivoltmeter when connected to a thermocouple are shown in Fig. 3. It will be noted that, for all ratings above 20 mv, the response times are 16 seconds or less.

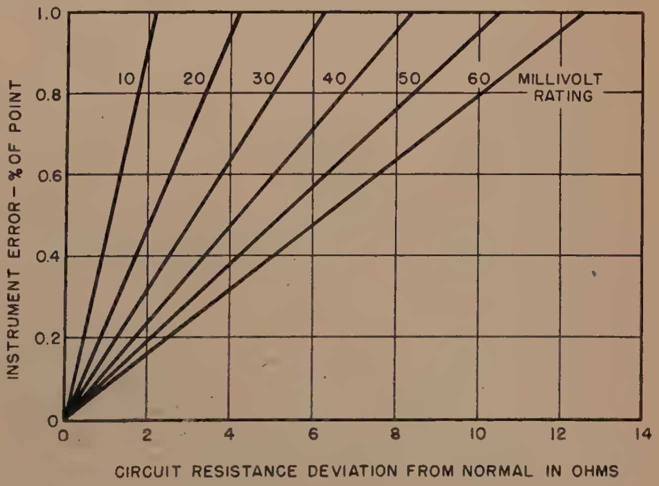


Fig. 4. Possible errors from change in resistance of leads of primary detector

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)Numbered references are listed at the end of the article.

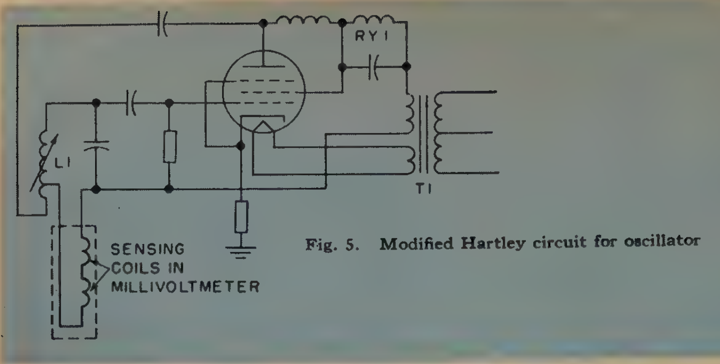


Fig. 5. Modified Hartley circuit for oscillator

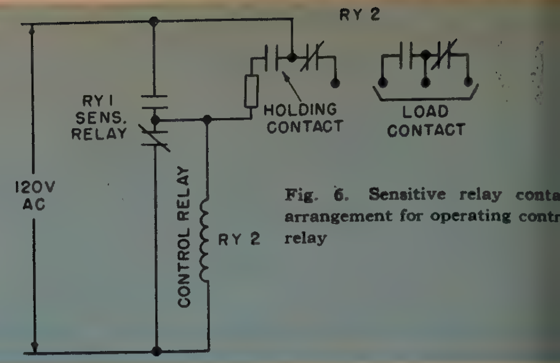


Fig. 6. Sensitive relay conta
arrangement for operating contr
relay

Ideally, a change in the resistance of the leads or primary detector with time or temperature should result in little, if any, error in indication. For this reason, the instrument must have the lowest full-scale current consistent with torque requirements. Possible errors resulting from resistance changes are shown in FIG. 4.

Inherent ambient temperature errors in the instrument aggregate only −0.04 percent per degree C departure from a 25 C reference. The sources of such error and the approximate amounts contributed by each source are indicated in Table I.

TABLE I: ERROR FROM AMBIENT TEMPERATURE
(For a 50-millivolt Instrument)

Sources of Error as Temperature Increases	Typical Instrument Reading
(1). Weakened Spring	plus 0.040% per deg C
(2). Weakened Magnet	minus 0.052% per deg C
(3). Mechanical Changes	plus 0.002% per deg C
(4). Resistance Changes*	minus 0.026% per deg C

* Value, percent per deg C = 1.3 ÷ millivolt rating of instrument.

The values given here apply to a 50-millivolt instrument. Automatic cold-end compensation is built into the instrument by means of a bimetallic spiral connected to one of the control springs in the conventional manner.

Occasionally, an application requires circuit connections such that a potential exists between the instrument case and its moving system. The resulting electrostatic field inside the instrument may cause sizable errors in indication. The new instrument is provided with an electrostatic shield to prevent the occurrence of such errors.

Although the instrument considered in this article is not intended for military service, joint Army-Navy Specification JAN-I-6 provides a convenient bench mark of performance for severe overload tests. Limits of change allowed by the Specifications for momentary overloads of 10 times and repeated sustained overloads of 1.2 times full scale are one-quarter of one percent of full scale value, while the actual deviation recorded is less than one-tenth of one percent.

The Control Problem

The major objective in designing the automatic control unit is to provide a highly sensitive and reliable means for regulating the controlled variable without imposing any burden on the moving system of the
indicator. This is accomplished by means of an el
tronic circuit consisting essentially of a pair of adju
able high-frequency sensing coils, an oscillator, and
relay system (FIG. 1).

The sensing coils, which are part of the oscilla
tuned circuit, are positioned at the desired set-po
by means of a knob on the instrument case. As t
indicating pointer reaches the set point, the alumin
actuating vane fixed to the pointer passes between t
sensing coils, causing the oscillator tube current
decrease and drop out the sensitive relay *RY1* whi
in turn, drops out the control relay *RY2*. As indicat
the control relay may operate the furnace heating c
cuit either directly or through a built-in mercu
switch or an external contactor.

The sensitivity of the system, which in this ca
refers to the amount of change in vane position nec
sary to produce on-off operation, is a function of th
elements—the oscillator, the sensing coils, and t
sensitive relay.

The Oscillator

The oscillator, which is of remarkable simplicity a
sensitivity, employs a modified Hartley circuit (FIG.
with capacitance and inductance values selected
minimize the effects of variations in the transcondu
ance of the tube or in line voltage and frequency. T
operating frequency, which is not critical, varies ove
range of 3–5 megacycles. This results in a system wh
has excellent sensitivity and is at the same time co
pletely shielded from external effects, a combinati
of features not possible at higher frequencies. W
tolerances are thus permitted in the tuned circ
elements. Body capacity does not affect the circu
even when it is being adjusted with the millivoltme
cover removed.

The oscillator circuit is tuned by means of the sin
adjustable element *L1*. This adjustment is set so t
on-off operation occurs when the millivoltmeter poin
is in line with the set-point indicator—that is, when t
aluminum vane is between the sensing coils.

Simplicity of the oscillator is achieved by using
standard single-element Type 6SJ7 pentode which
sufficient output to operate the sensitive relay direc
without a stage of amplification. Since the circ
operates satisfactorily with tubes having a wide ra
of transconductance, selected tubes are not requir
and hence, maintenance problems are reduced. T

cuit is so designed that failure of the tube will cause : furnace to shut down.

e Sensing Coils

It is desirable that the sensing coils, which are a part the oscillator tuned circuit, yield a maximum change impedance as a function of vane position. To this 1, they are designed to operate at a high frequency; d a maximum concentration of the field between em is secured by using small coils backed up with tered magnetic core material and closely spaced thin the limits of mechanical clearance.

e Sensitive Relay

The manner in which the sensitive relay operates the ntrol relay is shown in Fig. 6. When the sensitive ay *RY1* picks up, the control relay picks up and ks itself in by means of a holding contact. *RY1* ist then shift to its fully dropped out position before can drop out *RY2*. This arrangement provides a posi- e on-off action which prevents chattering. The circuit o contributes to the long life of the sensitive relay cause it permits *RY1* to drop out *RY2* by short-circuit- ; its coil rather than by interrupting the coil current.

The choice of a sensitive relay is based upon two quirements: (1) it must be sufficiently sensitive to be erated directly from the oscillator plate circuit without amplification; and (2) the differential between its pick-up and drop-out currents must be a minimum. The relay chosen operates directly from the 6SJ7 pentode and has a current differential of only 0.3 milliampere. It has a life expectancy in excess of one million cycles and is hermetically sealed to exclude dirt and moisture.

The over-all sensitivity of the control system, which, as stated above, is determined by the characteristics of the oscillator, the sensing coils, and the sensitive relay, is shown in Fig. 7. As indicated here, a movement of 0.007 in., or 0.1 percent of full scale, in vane position produces the 0.3 milliamp change in oscillator tube current necessary for on-off operation of the sensitive relay.

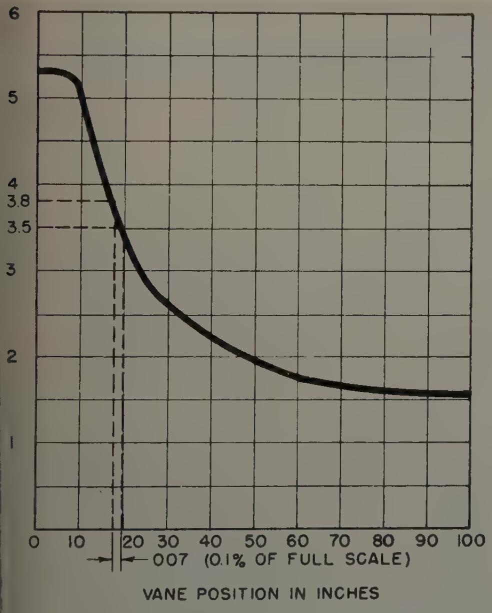


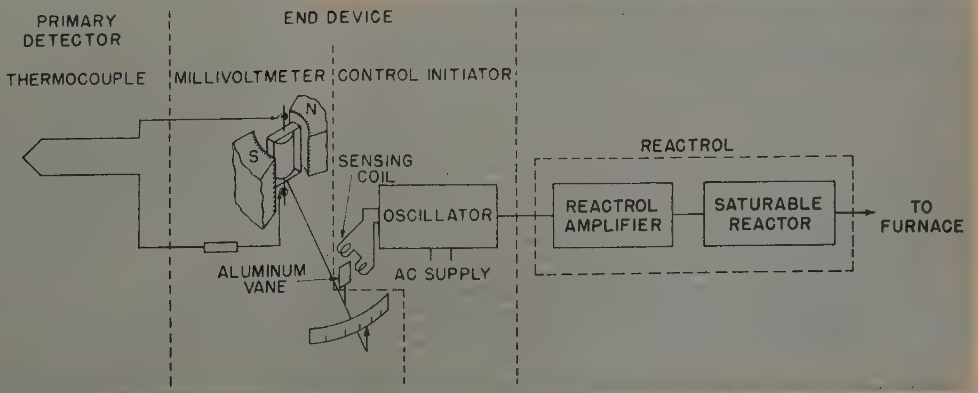
Fig. 7. Sensitivity of control system

Major Variations in Control Equipment

There are two basic types of control units provided with the new millivoltmeter, designated according to their respective functions as the Pyrometer Controller and the Pyrometer Protector. A unit which operates to maintain the average temperature at a certain set point or within certain set limits is called a "controller." One which acts as a safety device to keep the temperature from exceeding a set-point is called a "protector." The protector is always used in conjunction with some form of separate control unit and functions to shut the furnace down and keep it shut down in the event of failure of the controller. Pyrometer controllers may be subdivided into three groups: those providing two-position control; those providing three-position control; and those modified for use with a Reactrol* (proportional control).

Two-position and Three-position Controllers

The system illustrated in Figs. 1, 5, and 6 is that of a pyrometer controller having "two-position" action—that is, action in which the final control element is moved from one fixed position to another, a so-called "on-off" or "open-shut" action. This basic system can be modified to provide a "3-position" control—that is, action in which a final control element is moved to one of three predetermined positions, each corresponding to a definite temperature range. The three-position controller consists of two control units and a millivoltmeter equipped with two pairs of independently adjustable sensing coils.



. 8. Components of pyrometer livoltmeter and automatic con- ller in functional relationship to actrol unit

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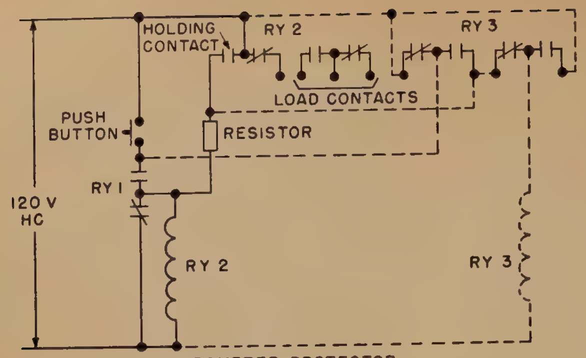

Fig. 9. Contact arrangement for sensitive relay, control relay, and push button of Pyrometer Protector

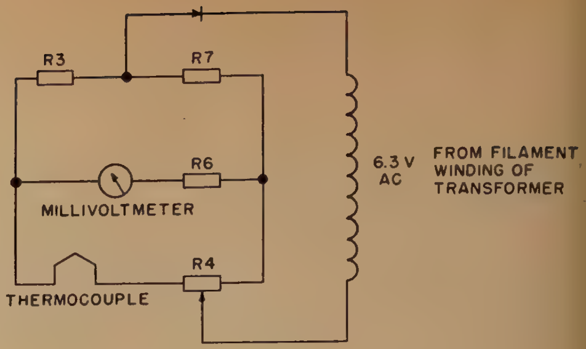

Fig. 10. Thermocouple-break protection circuit

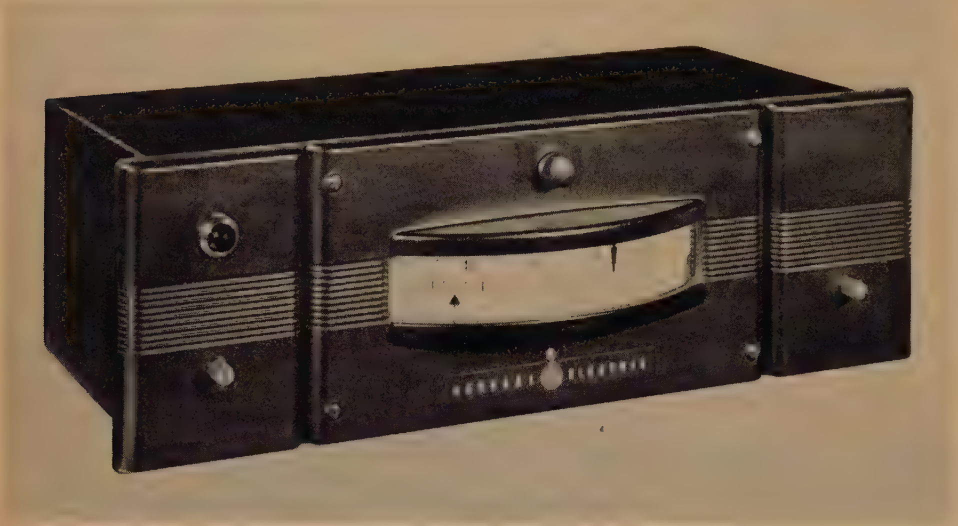

Fig. 11. External appearance of new pyrometer millivoltmeter controller

Controller for Use with Reactrol

Applications for which the effect of temperature cycling must be minimized require proportional control—that is, control in which the rate of heating is in proportion to the deviation of the temperature from the set-point over an adjustable range called the "proportional band." This form of control is provided by a pyrometer controller modified for use with a Reactrol unit. As shown in Fig. 8, this system differs from the two-position and three-position units in that the sensitive and control relays are omitted. The oscillator-tube current is used to generate a voltage signal directly controlling a Reactrol unit, which consists of an electronic amplifier and a saturable reactor in series with the heating load. The signal from the controller is proportional to the vane position in the proportional band and through the Reactrol varies load current proportionally.

Pyrometer Protector

The Pyrometer Protector, which prevents the temperature from exceeding a certain set-point, is designed for use as a safety device with separate, external control equipment. Its essential components are the same as those of the controller, with the addition of a push button. The connections for the sensitive relay, control relay, and push button are shown in Fig. 9. As indicated, the push button must be closed to permit the relay *RY2* to pick up, and thus the furnace remains shut down even after the temperature has dropped below the set-point unless the heating circuit is reclos manually.

Thermocouple-break Protection

A standard feature available on both protector a controller units is the thermocouple-break protecti circuit (Fig. 10) which causes the furnace to shut do when the thermocouple open-circuits. An instrume unprotected against this hazard would read ambie

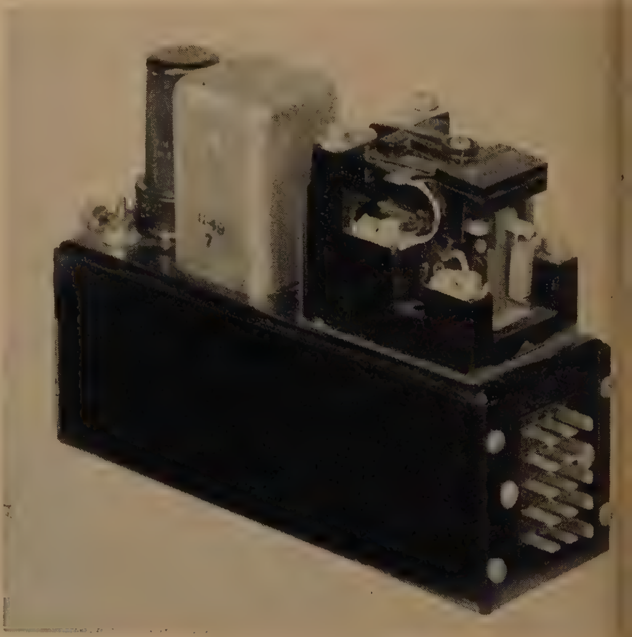

Fig. 12. Control unit

perature if the thermocouple should break. The :rol circuit would then function as though the iace were cold; that is, it would close the heating uit and keep it closed, thus allowing the tempera- to become excessively high. The thermocouple- ak protection circuit consists of a balanced bridge of ch the thermocouple circuit forms one arm and the ivoltmeter acts as a galvanometer. A rectifier in es with the filament winding of the transformer plies DC to the bridge. With the thermocouple uit closed, the bridge remains balanced and does affect the millivoltmeter indication. Should the rmocouple fail, however, the bridge becomes suffi- ntly unbalanced to cause the instrument pointer to ve upscale to the set point and shut down the furnace.

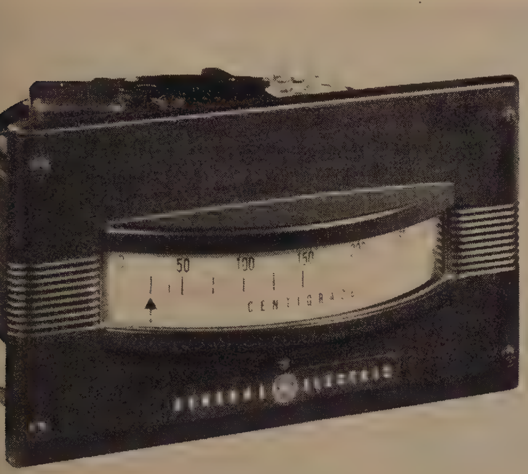

Fig. 13. Pyrometer indicator (millivoltmeter)

ernal Features and Mechanical Design

n appearance, the new pyrometer millivoltmeter troller combines attractiveness and utility (Fig. Its scale length (seven inches) provides for ease accuracy in setting and reading instrument nters. The case, which is tightly gasketed to prevent dust, dirt, or chemical fumes from reaching the instrument mechanism, is suitable for either flush or surface mounting. The millivoltmeter is housed in the center of the case with a compartment for a control unit on either side. In the Pyrometer Protector or the two-position Pyrometer Controller, each of which has only one control unit located on the right-hand side, the left panel is occupied by a red signal light which indicates either that the protector has shut down the furnace, or that the controller has closed the heating circuit, as the case may be.

Simplicity and ease of servicing were major considerations in the mechanical design of the new device. The control unit (Fig. 12) and millivoltmeter (Fig. 13) are both plug-in units which may be quickly and conveniently removed for checking or servicing. Entrance to the control compartment is gained simply by removing the front cover, thus providing easy access to the tube, tuning adjustment, balancing adjustment, and reset button.

Summary

The new indicating and controlling pyrometer described in this article represents a substantial contribution to the field of industrial instrumentation. Its range of application extends far beyond that of process temperature control mentioned here. Broadly speaking, it includes any situation in which on-off operation in response to a millivolt signal is required. Such features as a unique, fully directionalized alnico V magnet, spring-mounted jewels, a specially constructed shell-less armature coil and a simplified oscillator unit combine to give the device a simplicity, reliability, accuracy, and versatility outstanding among modern industrial instrument designs.

References

(1)"Mechanical Factor of Merit with Respect to Electrical Instruments," by J. H. Goss, General Electric Review, vol. 36, April 1933 p. 188.

(2)"Instrument Bearing Friction," by A. L. Nylander, General Electric Review, vol. 44, July 1946, p. 12.

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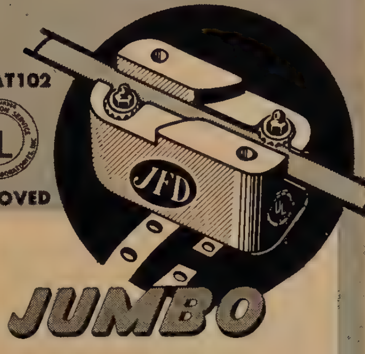
This lightweight radiation probe will be used in hospitals and laboratories where work with radioactive materials is being conducted



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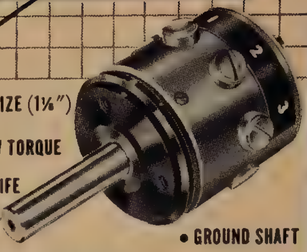

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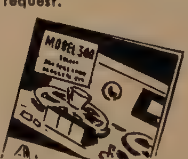

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dditional features make the new unit standing. It uses ribbon-type gas burners ch ignite quietly and go out quietly; safety pilot provides automatic shut-off as in case the pilot flame goes out. The t-transfer surface is the "pin-point" ting surface, its outside covered with dreds of slender iron projections over ch the air for heating passes to give er heat. Similar slender rods within the sages through which the hot combustion es pass serve to gather and conduct heat iently to the air passing over the heat- hanger surface. The new horizontal gas nace is designed specifically as the nace component of the Air-Wall ting system and may also be used for ventional forced-air systems. Two sizes offered at 90,000 and 120,000 Btu-per- r input. Units are AGA approved and listed by Underwriters' Laboratories.—*eral Electric Company, Air Conditioning ., Bloomfield, N. J.*

Resonant Flip-Flop

A replacement, known as the CRC ferroresonant Flip-Flop, for the vacuum tube in certain medium-speed counting, amplifying, and control applications. This component is a bistable-state device which is equivalent to a single vacuum tube Eccles Jordan trigger circuit. It resembles a saturable reactor and operates at frequencies up to 20 kc. It has no filament to burn out and occupies about one-tenth the space of a comparable vacuum tube. As an amplifier it produces a high power gain. It is immune to acceleration and shock and will operate for years without servicing. Operating on approximately 10 percent the power needed by an equivalent vacuum tube, it delivers 90 percent of input energy as usable output. There is virtually no problem of heat dissipation. Design of the unit is very flexible and can be adapted to a large number of uses.—*Computer Research Corp., Torrance, California.*

Step-motor Impulse Counter

A step-motor impulse counter, newly designed to provide one hundred percent accuracy up to 60 counts per second, has been recently announced. Designed to cover counting ranges above those possible with electromechanical counters and below those in which scalers are normally required, the device has a counting range which makes it especially useful in high-speed production counting. It may be used in such applications as counting the number of vitamin pills produced by a factory or counting flaws in fabric at process speed. The counter can be used also in certain types of radiation counting where the use of a direct-reading register is desirable.

The device consists of a step motor with a resetting-type register and a power supply enclosed in a steel case. The step motor and register assembly are mounted on the power-supply enclosure, which contains an electronic switch and a high-voltage supply capable of supplying the power requirements of a phototube preamplifier. The counting assembly can be easily removed and placed in a remote position such as a control panel. This impulse counter is rated at 0–60 counts per second; but the two-phase step motor provides a high degree of accuracy even at counting rates in excess of 100 counts per second. Over-all dimensions of the counter are 13 in. by 11 in. by 7 in. It weighs approximately 12 lb and operates on 115 volts, 60 cycles.—*General Electric Company, Special Products Division, Schenectady, New York.*

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ERNATIONAL BIBLIOGRAPHY ON ATOMIC

RGY—Vol. 2: Scientific Aspects—Com-
d by Atomic Energy Commission Group,
t. of Security Council Affairs, United
ions (Columbia University Press, New
k, Official Distribution Agent). 1951.
00.

his two-inch-thick volume is an admir-
listing of a large number of the papers
echnical literature dealing with our
wledge of the atomic nucleus and with
lications thereof. Only papers appearing
he past quarter-century (1925–1949)
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y are divided up into 90 subject head-
, one of which (Cosmic Rays, Meson
sics, and Astrophysics) includes 2200
les, others of which (Isotopes in Agri-
ure and Ecology) contain less than 100
ers. Unfortunately for the physicist,
s the biological subjects which are
t thoroughly subdivided. Under each
ect heading the articles are arranged
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s long, which makes it easy to check
individual's contributions to the field.
e is also a 30-page list of the abbrevia-
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J. R. STEHN

THE BEHAVIOR OF ENGINEERING METALS

H. W. Gillett—John Wiley & Sons, New York. 1951. 395 pp. $6.50.

The book is addressed to "those who are not metallurgists but who participate in the selection of metals and alloys for engineering uses." It is the last work of a respected metallurgist, whose recent death terminated a long and useful career. He has attempted to present the problems, the background, the philosophy, and typical solutions in the selection and use of engineering metals. An informal, often colloquial, style is used, making the text suitable for casual reading. Close reading reveals many grammatical errors, obscure meanings, poor organization and, at times, the assumption that the nonmetallurgist reader has a metallurgical background. Despite its deficiencies in presentation, the book is technically sound, has a worthwhile objective, and should prove useful to its intended audience.

ROLAND P. CARREKER, JR.

POLYPHASE COMMUTATOR MACHINES

B. Adkins and W. J. Gibbs—Cambridge University Press, New York. 1951. xiv+224 pp. $4.00.

This book is devoted to the entire family of commutator machines in which a polyphase alternating voltage occurs between the brushes, at either line or slip frequency. The authors first explain the operation of polyphase induction motors and generators in terms of equivalent circuits and circle diagrams and speed-torque relations; they then show how a-c commutator voltages can be injected into such circuits to obtain the speed and/or power-factor control which justify the use of the more costly and complicated polyphase commutator machines.

Explanations are presented of the theory, operation, construction, and application of series commutator motors with external current transformer, shunt motors of the brush-shifting type (Schrage) and also with external voltage regulator, Scherbius regulating machines, ohmic-drop exciters, phase advancers, self-exciting low-frequency generators, asynchronous condensers, variable-ratio frequency converters, and the Osnos motor. Related information is given on carbon brushes, special commutators and windings, hunting, and self-excitation.

A prior knowledge of induction motors and d-c machines is needed to follow the theoretical treatment, but most of this well-illustrated text is of a qualitative, practical nature which will be of great interest to many engineers and motor users who desire a general knowledge of a-c commutator machines.

There has long been a need for a book of this type. I heartily recommend it.

E. R. SUMMERS

ENGINEERING STATICS AND DYNAMICS

Dan H. Pletta—Ronald Press, New York. 1951. 392 pp. $5.50.

Mr. Pletta's purpose in writing a new book on elementary mechanics is to offer a way of "teaching the beginning student to think in terms of a few fundamental concepts." With that aim the reviewer is in complete sympathy.

Derivation of formulas should be reserved, says Pletta, until the student reaches the "design stage," and he therefore derives few. Although the number of literal expressions increases in later chapters, the author is more successful than most in the simplicity of presentation.

Noteworthy is the relegation in Chapter 7 of "Coriolis' acceleration" to its appropriate place as simply a term that appears in a proper analysis of motion.

ARVID L. ANTONSON

THE FISCHER-TROPSCH AND RELATED SYNTHESES

Henry H. Storch, Norma Golumbic, and Robert B. Anderson—John Wiley & Sons, New York. 1951. 610 pp. $9.00.

The book unquestionably represents the best critical review of the Fischer-Tropsch and related syntheses. Aside from this, however, the most important over-all contribution of the book is its excellent generalized treatment of contact catalysis.

Practicing chemists and chemical engineers will find the book especially useful for its concise treatment of heterogeneous catalysis as applied to catalyst preparation, analysis of catalyst by x-ray and electron diffraction and electron microscopy, determination of density, surface area and pore size, the use of tagged atoms, and methods of kinetic studies. There is also an excellent treatment of the thermodynamics of the

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BOOK REVIEWS (Continued)

Fischer-Tropsch reactions, which should serve as a guide to similar studies of other reactions. References are abundant to the original work on all these points for those desiring a fuller treatment than that given.

The major part of the book is devoted to specific developments of the Fischer-Tropsch reaction. Broadly covered are catalyst development, laboratory and industrial developments (especially those of Germany), variations in the process and their relative efficiencies and versatileness, and the related oxo, isoparaffin, and synol reactions. A very critical review is made of the proposed mechanism of the reactions, showing that a great amount of work yet has to be done before the chemist will understand the reactions of carbon monoxide and hydrogen over metal-oxide catalyst.

NEWELL C. COOK

ADVANCED FLUID DYNAMICS AND FLUID MACHINERY

R. C. Binder—Prentice-Hall, New York. 1951. 426 pp. $8.00.

Advanced Fluid Dynamics and Fluid Machinery is an excellent textbook. Dr. Binder introduces each new topic with basic concepts, such as Newton's laws or the conservation of energy or momentum principle, which are readily understood by the student. No higher mathematics other than calculus is required in the derivations, although some simplification in notation is accomplished through mathematical shorthand of vectors and tensors.

Material coverage extends beyond first college-course level. The three major sections include (1) one-dimensional flow, boundary-layer theory, turbulence; (2) fluid machinery such as jet pumps, fluid couplings, torque converters, turbines;
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COMMUNICATION NETWORKS AND LINE

Walter J. Creamer—Harper & Bros., N
York. 1951. 353 pp. $6.00.

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munications. With a little additional
struction, the material covered wo
provide a good course for undergradua
As a reference, it is particularly us
because of its conciseness.

The material covered includes meth
of circuit analysis; for example, Theven
Theorem, electric circuit filter theo
transformers as applied to communicat
networks, and circuits with distribu
parameters, such as transmission li
Each subject is liberally illustrated
numerical examples, which help consi
ably to clarify the subject matter.

F. H. WRI

INTRODUCTION TO THE THEORY OF C TROL IN MECHANICAL ENGINEERING

R. H. Macmillan—Cambridge Univer
Press, New York. 1951. 195 pp. $6.00.

Although not pretending to be an
clusive treatment of the field of se
mechanism, this book does present man
the elementary concepts of control, i
clear and simple manner. Especially g
is the treatment given to the transfer fu
tions and transient performance of i
vidual components. Each chapter is supp
with a quantity of problems, with ansv
provided as a convenient check.
American reader, however, will have
tolerate the use of terms more familia
England than here.

MURRAY ROSENBL

TV MASTER ANTENNA SYSTEMS

Ira Kamen and Richard H. Dorf—John
Rider, Publisher, New York. 1951. 356
$5.00.

This appears to be a thorough treatm
of a subject which will become increasi
important in the television industry.
covers the various antenna systems and
stallation techniques with praisewor
detail, and describes the legal and techn
pitfalls that could plague installation
service organizations.

The book contains much informat
both general and technical, and is com
hensive and well written. It can be
sidered a valuable addition to a techn
library.

W. L. PARKIN

STRENGTH OF MATERIALS

Max M. Frocht—Ronald Press, New Y
1951. 439 pp. $5.50.

Professor Frocht has so successf
built into this work great interest, p
ticality, and completeness that it prom
to become a widely accepted text
students of elastic analysis. The bo
objective, prevention of failure by exces
deformation or fracture while most e
tively utilizing materials, gives a prac
reason for studying strength of mate
that will automatically stimulate stu
interest. Because of this approach Profe
Frocht never deviates from the impor
hypothesis that strength of materia
only a means to an end—that is, the
cessful design of machinery and struct

An excellent physical picture of
stress and strain conditions occurrin
many different configurations is prov

Baking, drying, or heat-conditioning of industrial products in the 150° to 650° F. temperature range, is now simplified by the use of furnace-type Calrod heaters in standard panels for field assembling on pre-fabricated frames. Using both radiation and convection principles for rapid temperature elevation and precise holding requirements, radiant Calrod ovens produce results with shorter heating cycles, lower energy consumption, and little maintenance.

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photographs of photoelastic and metallic
specimens. Graphical methods or plots
experimental data furnish solutions to
blems beyond the scope of the book's
lytical methods. Analytical methods,
wing stress and strain conditions at a
nt, are handicapped by a lack of vector
lysis, but for the average undergraduate
was probably necessary. Mohr's circle
xplained and demonstrated thoroughly,
wing the relations existing between it and
analytical deviations.

he book is highly recommended to all
erested in the study of elastic analysis.
s easily understood, stimulating, and of
at direct use in design.

E. H. FREIBURGHOUSE, JR.

THEMATICAL ENGINEERING ANALYSIS

fus Oldenburger—Macmillan Co., New
rk. 1950. 426 pp. $6.00.

he mathematical representation of
sical problems, in a form that can be
veniently handled, is treated here.
ce the solution of the mathematical
ations is not considered, it is possible
a modest-sized book to include funda-
ntals of all the major branches of engi-
ring. The fields covered are: The
chanics of Rigid Bodies, Electrical
cuits and Fields (Maxwell's equations
used), Thermodynamics, Heat Trans-
Elasticity, and Fluid Mechanics. Guides
making reasonable assumptions are given
many types of problems. Dimensional
lysis is developed and applied.

knowledge of advanced calculus is
umed. Numerous problems are given,
ether with hints and answers. Many
erences are included. The book should be
able for a text or a reference.

GEORGE M. ROSENBERRY, JR.

NCHRONOUS MACHINES: Theory and Per-
nance

arles Concordia—John Wiley & Sons,
w York. 1951. 224 pp. $5.50.

n the past, the fundamental circuit
ory of the transient performance of
chronous machines has been widely
ttered in technical articles, so there has
n a need for a comprehensive book on
subject. Mr. Concordia's book satisfies
need. In an ably presented manner,
theory of transient performance is
eloped from first principles, so that the
avior of any synchronous machine can
predicted.

esides a comprehensive mathematical
lysis, a fundamental physical explana-
of machine performance is given. Thus
reader is well equipped to extend the
ory to tackle new problems.

DAVID BIRNSTINGL

CTRICAL INSULATION—Its Application
Shipboard Electrical Equipment

ham Lee Moses—McGraw-Hill Book
New York. 1951. 259 pp. $5.50.

his is an authoritative guide to the user
lectric equipment in the proper methods
inspection, maintenance, and repair
ts electrical insulation portions. This is
ticularly so because the author had the
operation of the major equipment manu-
urers. A complete primer on the funda-
ntal concepts, terms, properties, and
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TRADE LITERATURE

CAPACITORS—A guide to the selection and use of mica capacitors of the military, industrial, and transmitter type. Includes instructions on how to specify. The final 14 pages are devoted to Faradon capacitors. Sixty-four pages. Catalog 420.—*Cornell-Dubilier Electric Corp., South Plainfield, New Jersey.*

ENGINEERING IRONS—Useful tables, charts, and photomicrographs show how through the use of nickel, alone or in combination with other alloying elements, the engineering properties of cast-iron can be controlled to meet almost any reasonable combination of service requirements. Twenty-eight pages. Titled "Guide to the Selection of Engineering Irons."—*International Nickel Co., Inc., Dept. EZ, 67 Wall St., New York 5, N. Y.*

INSULATION PRODUCTS—Two bulletins on insulation, one covering Macallen built-up mica electrical insulation products—its properties, processing, and grading; and the manufacture, advantages, and types. Twenty pages; Product Bulletin No. 527A. The other bulletin contains data on Dieflex tubing and sleevings used to insulate leads and wires in electrical equipment. Eight pages. Product Bulletin No. 250A.—*Insulation Manufacturers Corp., 565 West Washington Blvd., Chicago 6, Illinois.*

METALLIZING GUNS—Two metallizing guns—Type 4E for machine-element work, and Type 5E for corrosion-protection coatings—are described in their own respective bulletins wherein emphasis is placed on five main features. Four pages each. Bulletins No. 94 and 95, respectively.—*Metallizing Engineering Co., Inc., 38-14 30th St., Long Island City 1, New York.*

PHOSPHATE TREATMENT FOR METALS—Describes Anchorite 100, a paint-anchoring corrosion-resistant phosphate treatment for metals. Attractively printed in two colors, the booklet describes the common causes of paint failure and how they can be prevented. It then goes into methods of application—immersion and spraying—of the Anchorite 100 treatment. Eight pages.—*Octagon Process, Inc., 15 Bank Street, Staten Island 1, N. Y.*

SCRAP IRON PROGRAM—Aimed to help increase the current dangerously low iron and steel scrap inventories in this country, "Scrap for Steel Mills and Foundries for Defense" emphasizes that with the current record-breaking steel production and large-scale expansion of production capacity, some plants have only a few days' scrap supply on hand. A program outlined in the booklet for recovery of dormant scrap suggests procedures for large industrial plants. Fifteen pages. NPA-BP-230.—*U. S. Department of Commerce, National Production Authority, Washington, D. C.*

VOLTAGE REGULATORS—Describes in detail the workings of a Stabiline automatic voltage regulator in maintaining a constant output voltage regardless of fluctuations in a-c input line voltages and changes in output load. Each standard regulator is illustrated and performance data given. Twelve pages. Bulletin S135.—*Superior Electric Co., Bristol, Conn.*

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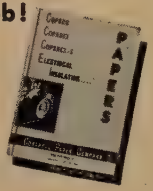

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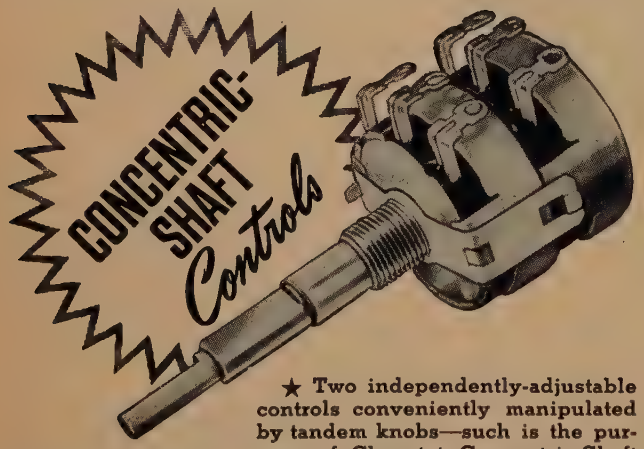

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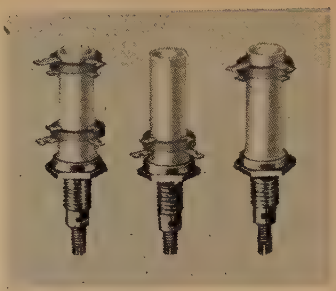

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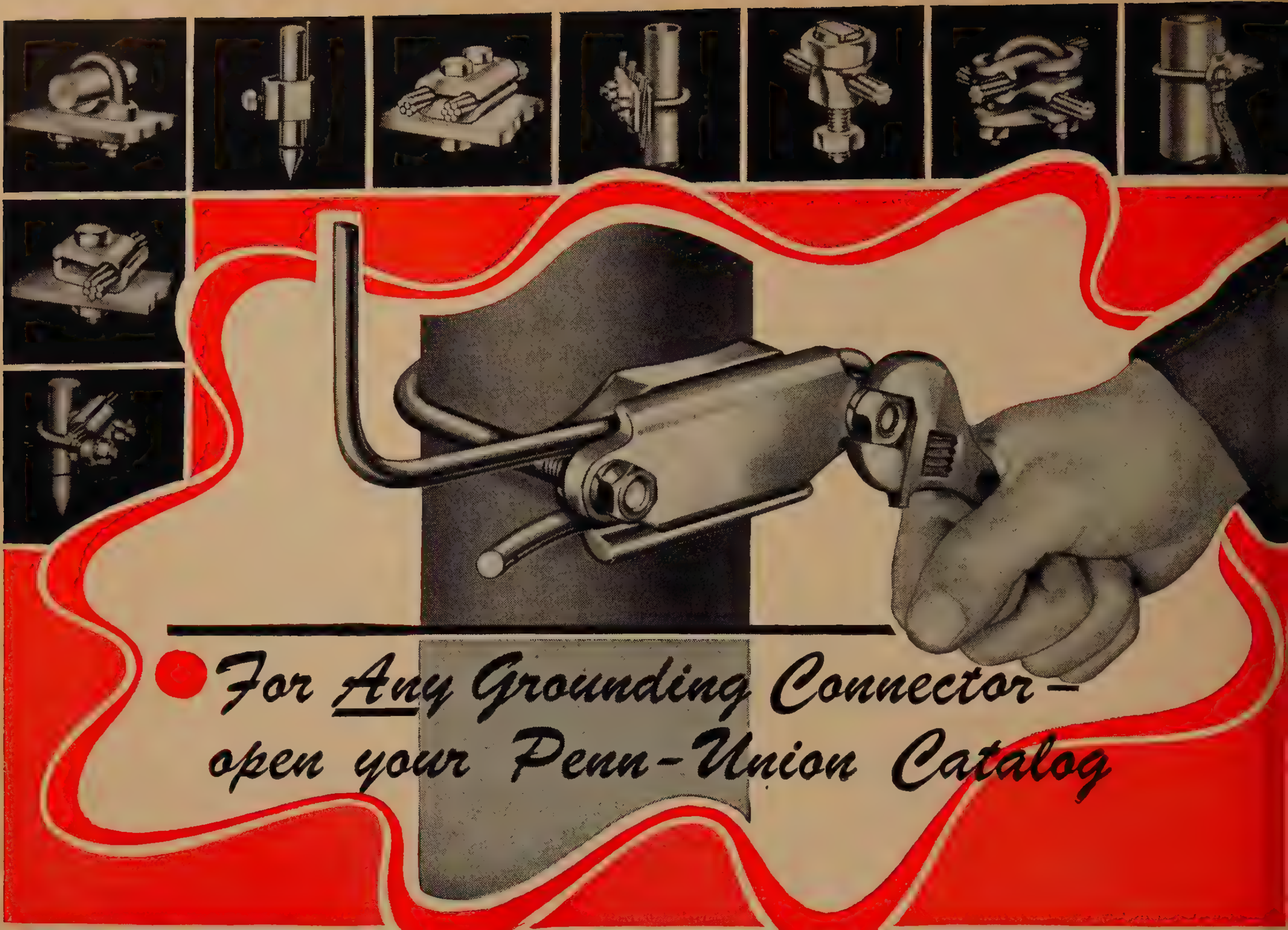

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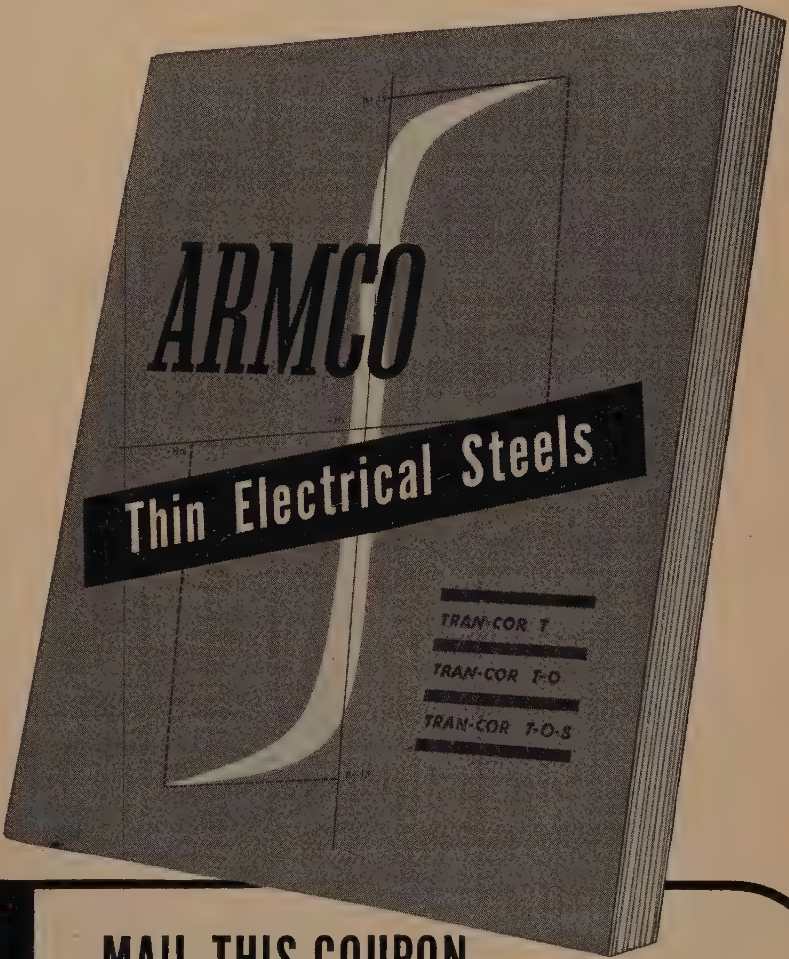

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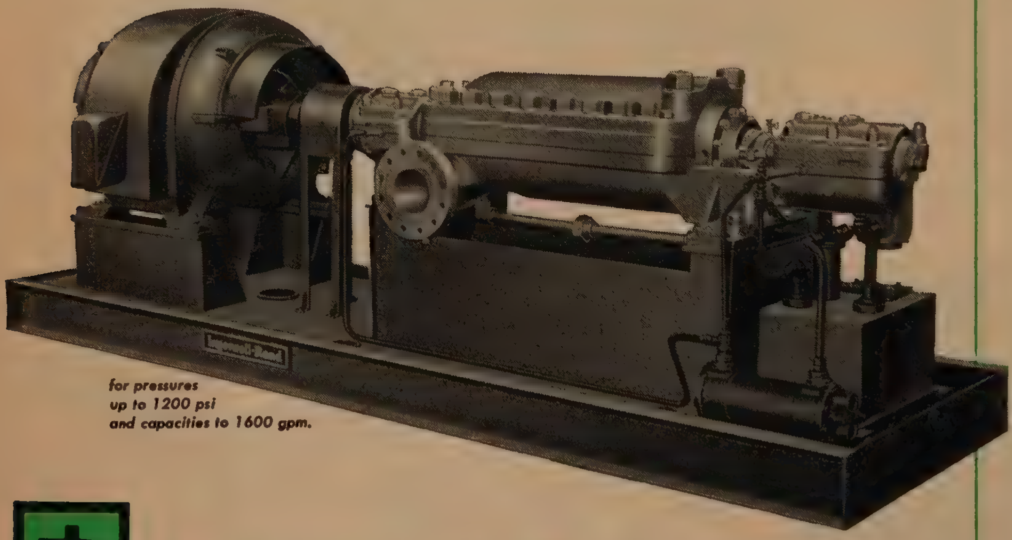

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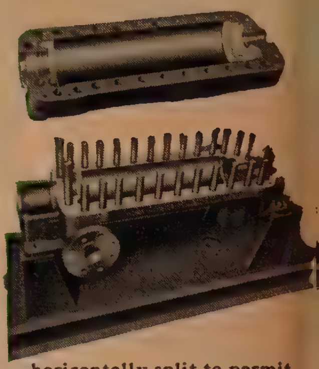

—horizontally split to permit access to rotor assembly without disturbing piping connections.

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—including impellers, wearing rings, and stationary channel rings with interstage liquid passages. All elements self-aligning, all precision-machined for high sustained efficiency.

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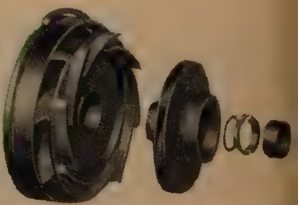

—assures complete radial balance of impellers over entire range of pump operation.

These and many other new HMTA features add up to:

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Servel goes electric with NICHROME*

Now the famous silent Servel refrigerator operates on elec-
city. In the new refrigerator, a simple electric heating element
ovides heat for operating this absorption-type system. Just
ug it in, and the new Servel goes to work . . . provides the
undless performance for which it is famous.

Since cold is obtained without a single moving part by means
heat applied to the system, the small heating element is the
al part of the new Servel. Every operation of the refrigeration
cle, indeed, depends upon the heater unit *staying on the job*.

Because of this, Servel has adopted heating elements made
h Nichrome—the electrical resistance alloy that is the very
art of quality appliances everywhere. Remarkably resistant to
gh heat and corrosion, and able to retain its physical and elec-
cal properties despite thermal shock resulting from intermittent
eration day in and day out, Nichrome assures Servel of
cient operation and a lifetime of dependable service.

Whatever *your* requirements for electrical resistance mate-
l, it will profit you to consult with us. In addition to world-
nous Nichrome and Nichrome V, we produce over 80 alloys
meet the varied needs of the electrical and electronic fields.
though strategic materials and the alloys we make from them
on strict allocation at the present time, we'll be pleased to
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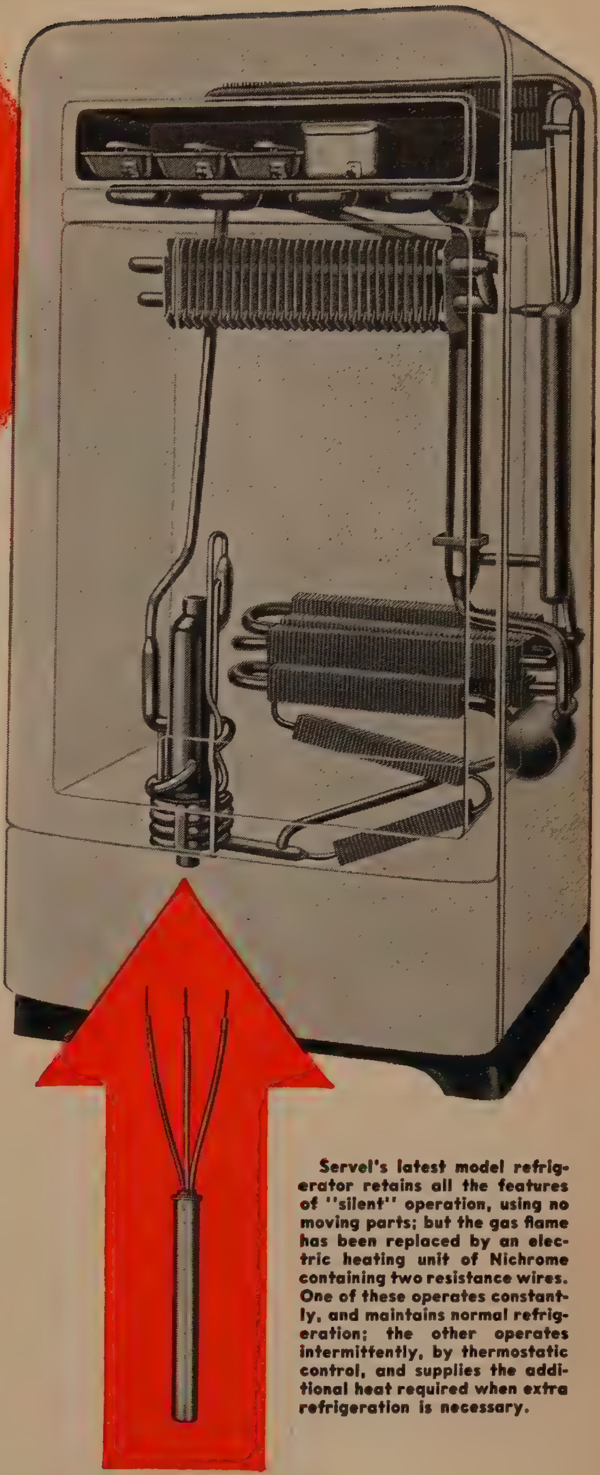

Servel's latest model refrigerator retains all the features of "silent" operation, using no moving parts; but the gas flame has been replaced by an electric heating unit of Nichrome containing two resistance wires. One of these operates constantly, and maintains normal refrigeration; the other operates intermittently, by thermostatic control, and supplies the additional heat required when extra refrigeration is necessary.

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* T. M. REG. U. S. PAT. OFF.

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They keep coming back for more

One thing that distinguishes a boiler from most other types of equipment is that its *annual* operating cost is more than its initial cost. In fact, the annual cost of *fuel alone* for the average boiler installation usually *equals* or *exceeds* the purchase price — and the purchase price of a boiler represents a sizable capital investment.

With fuel costing what it does today, it is more important than ever before to select a boiler that will assure the most efficient performance possible. That is why it is especially significant that people who have bought C-E Vertical Unit Boilers — and know these boilers *through their own experience*— continue to buy them.

Just glance at the examples at the right. It's just a small sample of the plants — in industry after industry — that have ordered and *reordered* VU Boilers.

Why not investigate the VU Boiler for *your* next installation. Our recommendations as to the most suitable type of VU Unit for your particular requirements are available to you or your consultants without obligation.

A Chemical Company ordered two VU Boilers in 1939. In 1946 five more were ordered for three of their other plants. In 1949 two more were ordered for one of these same plants, and in 1950 two more units for a fifth plant. In 1951 three more units were ordered for still another plant — thirteen units for six plants in twelve years!

A Steel Company now has a total of eleven VU Boilers in four different plants. Starting with three units in 1936, it has reordered three times . . . most recently in the fall of last year with an order for three more units.

A Textile Manufacturer ordered two VU Units in 1936. Another unit was installed in 1940 and a third in 1944. Still another textile company installed one unit in 1945, a second in 1949 and has just ordered another.

An Electric Utility Company installed its firs VU Unit in 1941. Two more units were ordere for another plant in 1947, a unit for a thir plant in 1946 and still another for a fourt station in 1949.

A Refining Company ordered one VU Unit i 1937, another in 1940 and another in 1949 fo one of its plants; also two in 1942 and one i 1947 for another plant. B-48

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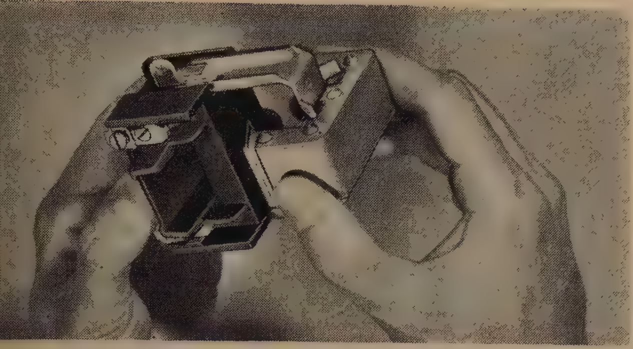
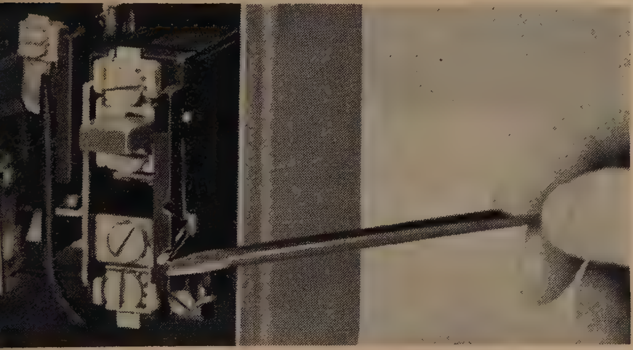


Kelly: *"There doesn't seem to be any wear on the moving parts."*

3 That's right. The moving structure is rugged and basically simple. There's no metal-to-metal friction between magnet and coil; thus, little or no wear. And the "molded-in" lubricant in the coil keeps the magnet operating smoothly and quietly for life.

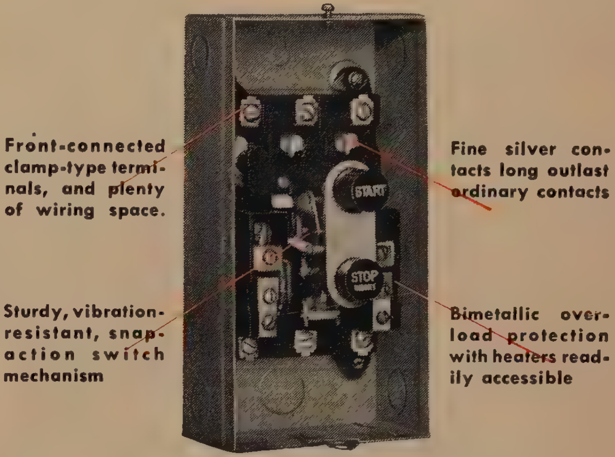


Kelly: *"Overload protection means a lot; I certainly don't want any burned-out motors these days."*

4 Those overload relays will give your motors all the protection they'll ever need. They are reliable and never need any attention. Heaters are in front and can easily be changed without disturbing any wiring.

MANUAL STARTERS, TOO . . .

For infrequent starting of 7½ hp or smaller motors, you can't beat a G-E manual starter for economy and dependable operation. . . Built to the same rugged specifications as the magnetic starter, it includes many of the same features for long life and easy upkeep.


Front-connected clamp-type terminals, and plenty of wiring space.
Fine silver contacts long outlast ordinary contacts
START
STOP
Sturdy, vibration-resistant, snap-action switch mechanism
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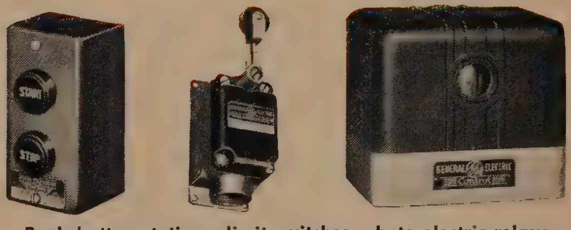

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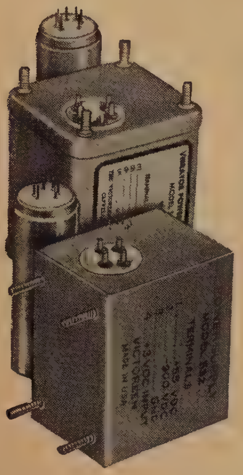

. . . four newcomers to their catalog of quality components and instruments for the electronic and radiation-measurement fields.

Victoreen has developed two high-efficiency lightweight vibrator power supplies for use with battery-operated portable equipment such as Geiger counters, photo-multipliers, and electronic equipment requiring a 900 volt supply. These compact units have been potted and hermetically sealed to make them reliable and rugged. They contain regulator circuits to stabilize their output and have a plate voltage output to operate electronic circuits. Net weight is only one pound.

- THE MODEL 517 VIBRATOR POWER SUPPLY operates from 4.5 volts of battery and supples +900 volts at 5 microamps and +55 volts at 0.25 ma.
- THE MODEL 532 VIBRATOR POWER SUPPLY operates from 3.0 volts of battery and supplies −900 volts at 15 microamps and +55 volts at 0.25 ma.

The precision vibrators which are used in these power supplies are available separately. They have been mounted in sponge rubber and hermetically sealed, and are available for such applications as highvoltage power supplies, portable Geiger counters, scintillation counters, and portable radios. These plug-in units weigh only 2½ ounces.

- THE MODEL 531 VIBRATOR is designed to operate from a 1.5 or 1.3 volt battery and requires a minimum of 18 milliwatts driving power.
- THE MODEL 542 VIBRATOR is also an 18 milliwatt unit but designed for operation in series with the primary of a transformer and from a 1.5 to 6 volt battery.

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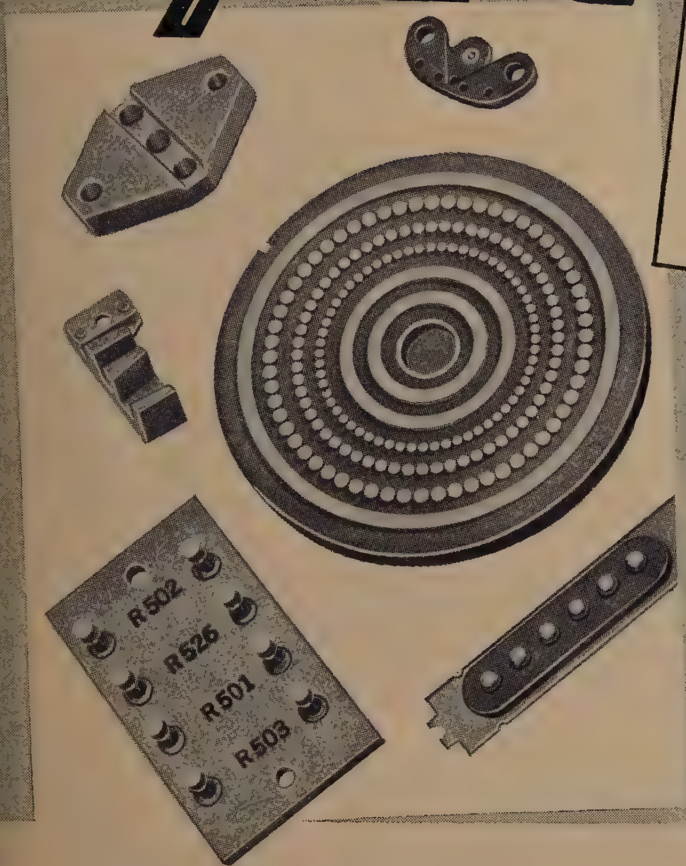

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DIELECTRIC CONSTANT, 1 MC	7.4	9.2	6.9
LOSS FACTOR, 1 MC	0.013	0.014	0.084
DIELECTRIC STRENGTH, volt/mil	500	400	400
VOLUME RESISTIVITY, ohm/cm	2×10^{15}	1×10^{15}	5×10^{14}
ARC RESISTANCE, seconds	300	250	250
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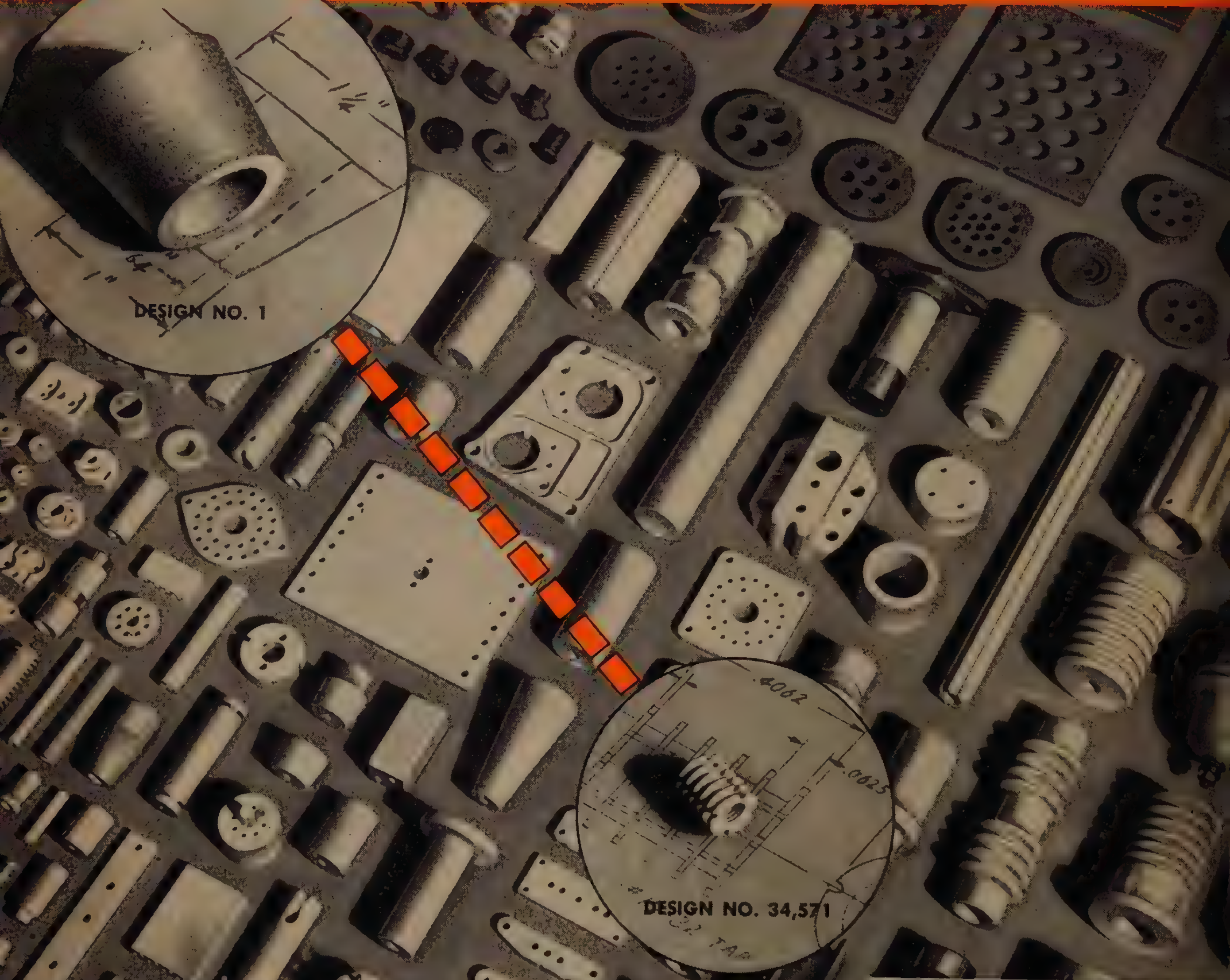

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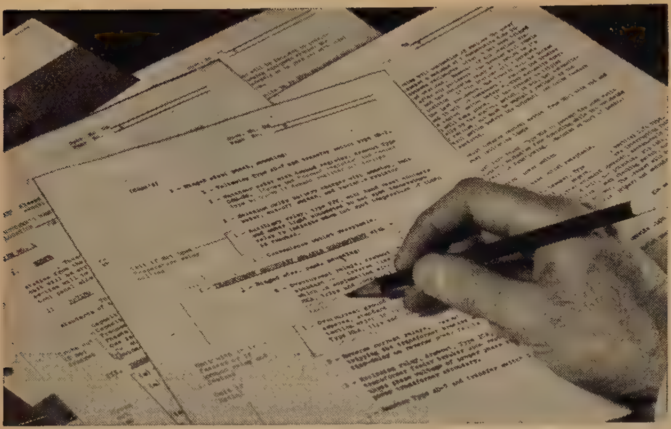

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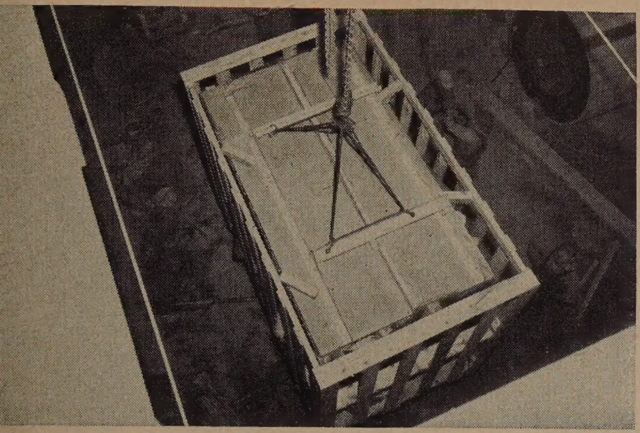
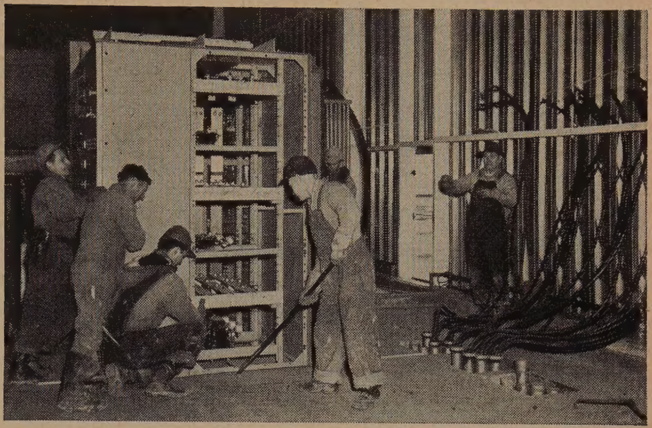


EASILY HOISTED OR PUSHED TO CONVENIENT LOCATION. Part of flexibility is ease of movement as well as adaptability. In photo ove, complete metal-clad switchgear unit is hoisted to roof.



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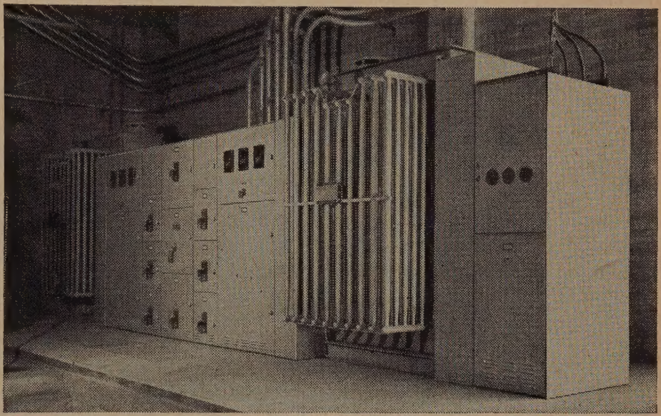

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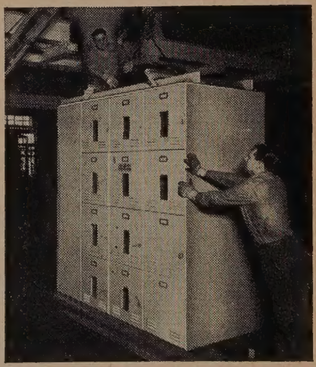

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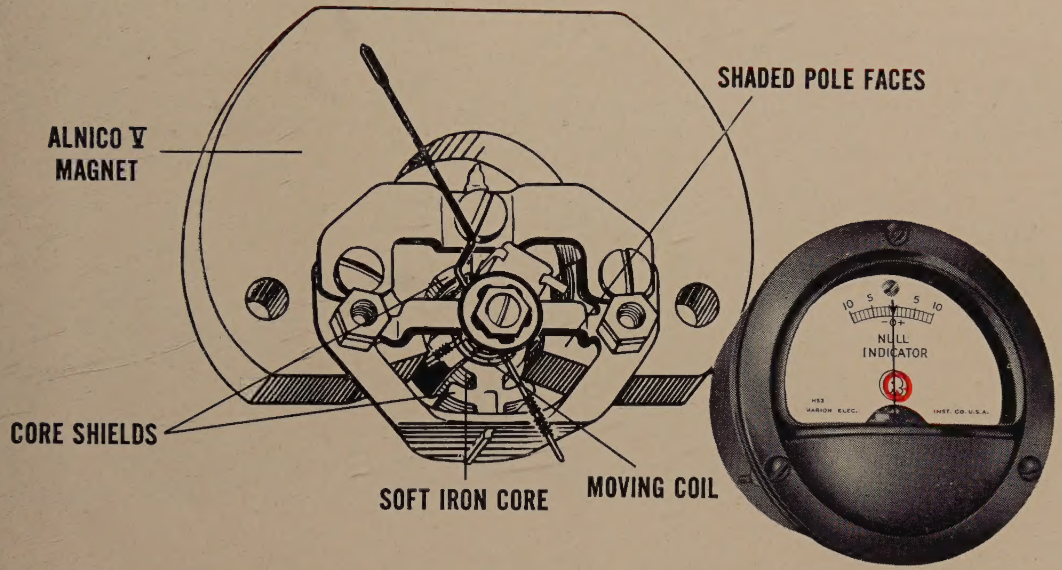

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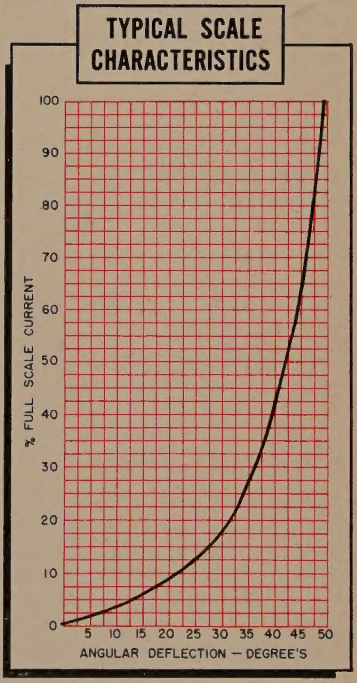

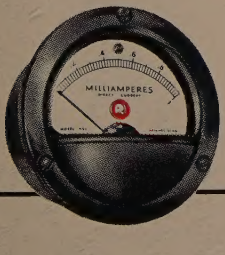

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